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Drift dominated InP/GaP photodiodes

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Abstract

We present InP photodiodes fabricated on GaP substrate with unique drift dominated design, which can build an electric field throughout the active region by varying the doping concentration. The InP/GaP photodiodes have been grown, processed and characterized. The excellent spectral response, higher than 75% internal quantum efficiency in UV and visible range, demonstrates the robustness of our drift dominated devices and superior performance with even relatively low quality material.

Keywords: Drift dominated; InP/GaP; Quantum efficiency; Photodiode

1. Introduction

With high mobility, high electron saturation velocity, high absorption coefficient just above the bandgap, and superior radiation resistance, InP is an attractive material for many applications such as HEMTs, HBTs, photodetectors and solar cells. Currently, one important technical challenge in developing InP devices is to overcome the friability and high cost of InP substrate. Many researchers in this area have focused on growing InP on Si substrates due to the low cost and robustness of Si substrate and the potential of integrating InP devices with current Si technology. Researchers have used various approaches such as wafer bonding, and epitaxial growth trying to improve the material quality and reduce the density of dislocations resulting from lattice mismatch and different thermal expansion coefficients between Si and III–V compounds [1–3]. We have a different approach. In addition to trying to improve the material quality, we focus on the device design so that our device is robust and its performance is less affected by dislocations and other defects.

2. Device design and structure

In our design, we collect the carriers generated by photon absorption by drift created by an electric field throughout the active layer instead of by diffusion associated with normal PN junction diodes. Besides the fact that drift dominated devices are more efficient and faster since carriers generated in the drift region can all be collected due to internal electric fields, drift dominated devices are expected to be more robust and less affected by dislocations as well. This is because normal PN junction devices, whose collection efficiencies rely on minority carrier diffusion, will be largely degraded due to degradation of minority carrier diffusion length with the generation of dislocations. The drift dominated devices, on the other hand, will be less affected since the carrier collecting mechanism is independent on the minority carrier diffusion length and photogenerated carriers will be transported rapidly with a high drift

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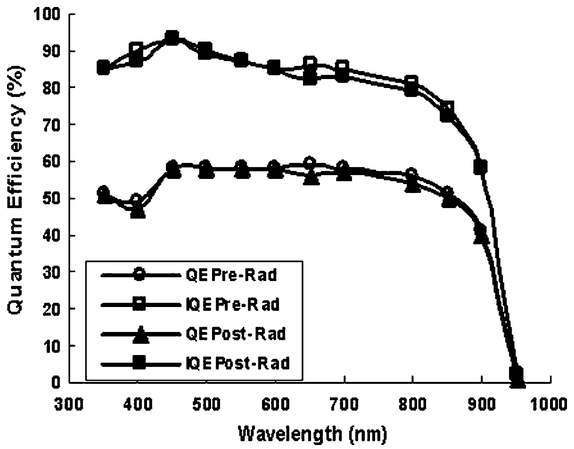

Fig. 1. Quantum efficiency versus photon wavelength for drift dominated InP solar cells before and after irradiation with 10^{15} cm^{-2} 1 MeV electrons.

velocity under a large electrical field. As a result, they will reach the other side of the junction within very short time and contribute to the photocurrent before trapped by the dislocations and defects.

The robustness of our drift dominated devices can be further demonstrated by the quantum efficiency measurement on drift dominated InP solar cells [4] before and after irradiation with 10^{15} cm^{-2} 1 MeV electrons which is shown in Fig. 1. The open circles represent the measured external quantum efficiencies before the irradiation, and the solid triangles are quantum efficiencies after the irradiation with 10^{15} cm^{-2} 1 MeV electrons. The squares represent the internal quantum efficiencies derived from the measured external efficiencies and the theoretical value of InP reflectivity as a function of wavelength. We can see from Fig. 1 that the quantum efficiencies are almost the same from UV to infrared before and after the high energy electron irradiation, i.e. the irradiation has essentially no effect on the cell response, indicating that our drift dominated devices are very promising to have superior performance with even poor material.

Before developing the growth of InP on Si, we first try the growth of InP on GaP since later we could use GaP as a buffer layer between InP and Si due to the fact that GaP is lattice matched to Si, while InP is 8% lattice mismatched to Si. By growing InP on GaP substrate, we can get an idea about the defect density and device performance due to the 8% lattice mismatch. The schematic layer structure of our drift dominated InP/GaP photodiode is shown in Fig. 2. By varying the Si doping concentration from 10^{16} cm^{-3} at the junction to 10^{20} cm^{-3} at the surface, we can achieve drift field in the order of 10^4 V/cm in the 100 nm n-type quasi-neutral region in the top layer. The 250 nm intrinsic InP layer is

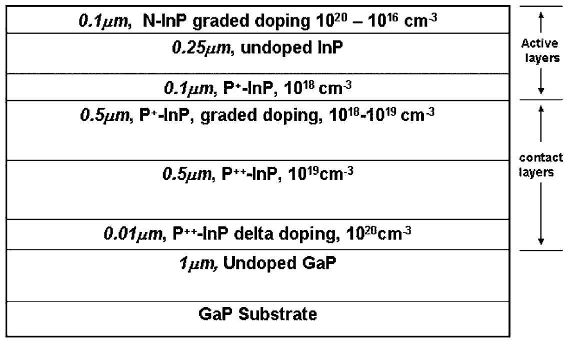

Fig. 2. Schematic layer structure of drift dominated InP/GaP photodiodes.

fully depleted where another large drift field of about 4×10^4 V/cm exists. Therefore all together we have drift field larger than 10^4 V/cm in the top 350 nm region, which is the active region of the device. We have designed the active region to be very thin because the carrier transit time in the region is proportional to the square of the region thickness. In order to have the carriers moving fast enough to avoid being trapped by the defects and dislocations before they reach the other side of the junction, we need to keep the active region as thin as possible. However, the thinner the active region the less illumination power that can be absorbed, which results in lower device efficiency. Therefore, we need a material with very high absorption coefficient such that we could keep the active layer thin without losing much power. InP as a direct bandgap material has very high absorption coefficient from just above the bandgap, and most illumination can be absorbed in a very thin layer. Fig. 3 shows the percentage of illumination being

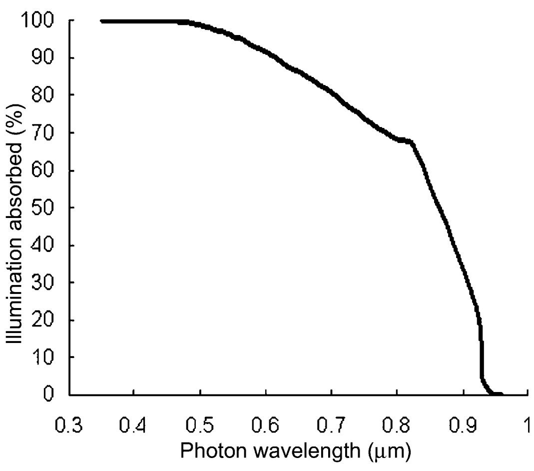

Fig. 3. The percentage of illumination absorbed in InP of 350 nm as a function of photon wavelength.

absorbed in the 350 nm InP drift region for different photon wavelengths. It demonstrates that most illumination with wavelength less than 850 nm can be absorbed in the active region. Besides the active layers, the 1000 nm heavily doped p-InP layers are expected to provide good ohmic contact. The structure has an additional advantage as a result of the high doping level at the surface. In conventional devices there is usually a reverse band bending region of about 10–100 nm in thickness at the surface due to surface Fermi level pinning, which drives photogenerated carriers away from the p–n junction. This can greatly reduce the blue-UV response of most devices, since the absorption coefficient for this photon energy range is usually above 10^5 cm^{-1} for most materials. However, for the high doping levels at the surface of our InP/GaP photodiodes, this region is less than 5 nm. Hence, a good responsivity in blue-UV spectral range is expected.

3. Experiments and results

The InP/GaP wafer was grown by the solid source MBE, of which beryllium was used as the p-type dopant and silicon was used as the n-type dopant for the InP epitaxial layers. The GaP substrate used was purchased and was n type doped with sulfur of concentration around 1×10^{18} cm^{-3}. The growth temperature was around 430 °C and work for this growth is patent pending. The corresponding AFM image is shown in Fig. 4. The AFM image shows that the surface roughness of the InP/GaP wafer is 2.48 nm. The devices have been processed and metallized as follows: samples have been etched down to the heavily doped p-InP contact layers by using hydrochloric acid and nitric acid, the 200 nm AuZn alloy (5 wt.% Zn) has been put down for p side ohmic contact, annealed at 410 °C in nitrogen for 90 s by rapid thermal annealing. Ti/Au (50/150 nm) has been used for the front contact. No heat treatment is necessary since the n-InP surface is pinned near the conduction band [3] and the doping level at the front surface is very high. All metal contacts were deposited by e-beam vacuum evaporation and were fabricated by lifting off the photoresist. The total area of the device is 0.25 cm^{-2} and the front side Ti/Au interdigitized contacts take about 5% of the device area.

After processing, we have profiled the carrier concentration as a function of device depth by using electrochemical *C–V* profiler and done the current–voltage characterization, and quantum efficiency measurement as a function of photon wavelength.

4. ECV carrier concentration profile

We used the electrochemical *C–V* profiler (ECV) to obtain the carrier concentration as a function of depth. The system has an electrochemical capacitance–voltage (*C–V*) measurement system that can derive the carrier concentration from *C–V* measurements as a function of depth in the sample. In this system, instead of using Schottky-metal ohmic contact for the *C–V* measurement, we use a conductive electrolyte solution which is 0.2 M EDTA mixing with ethylenediamine. And we employ variation of the voltages on the electrolyte cell, which leads to dissolution of the semiconductor, therefore the semiconductor can be repetitively etched and measured, leading to a very accurate measurement of carrier concentration versus depth in the sample. Our ECV carrier doping concentration profile is shown in Fig. 5. The first data point of the profile which was measured before the sample was etched shows the hole concentration of 1.24×10^{19} cm^{-3} at 8.2 nm from

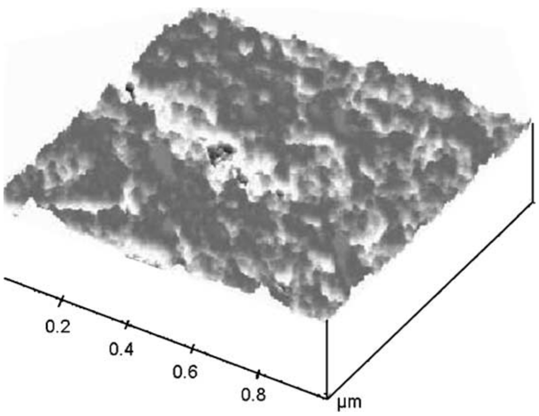

Fig. 4. AFM image of InP/GaP wafer with surface roughness of 2.48 nm.

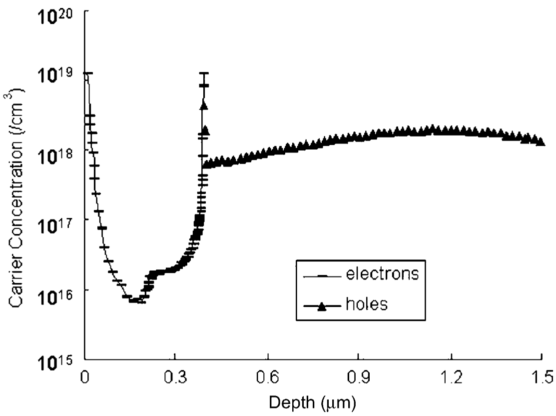

Fig. 5. ECV carrier concentration profile of InP/GaP photodiodes as a function of device depth.

surface, thereby demonstrates the thin depletion region (8.2 nm) from the surface due to the very high doping level 1.24×10^{19} cm^{-3}. The profile also shows the drift region by the linearly graded n-type doping from 10^{19} to 10^{16} cm^{-3} in 100 nm and shows the intrinsic InP region from 100 to 350 nm.

5. Current–voltage characteristics

The dark current voltage characteristics for the InP/GaP photodiodes are shown in Fig. 6 by using semiconductor parameter analyzer HP4156. Two probes have been placed on the metal bars of the front contact and the back contact respectively from which the voltage has been applied and the corresponding current has been measured. The voltage has been applied from −1 to 1 V. The ideality factor extracted from the *J–V* curve with the diode area of 0.25 cm^{-2} in the forward direction is about 2, and the reverse saturation current density (again extracted from the forward *J–V*) is 0.76 $\mu A/cm^2$, indicating that recombination current has been generated due to the dislocations and defects in the InP epitaxial layer. Also the leakage current increases quickly with the increasing of reverse biased voltage due to the short carrier lifetime in the depletion region resulting from the large defect density in the InP epitaxial layer.

6. Quantum efficiency

We measured the quantum efficiency as a function of wavelength by using 1000 W Quartz Tungsten Halogen Lamp focusing into the monochromator, and using 1 mm diameter core fiber to transmit the monochromatic light from the monochromator onto our device. We used

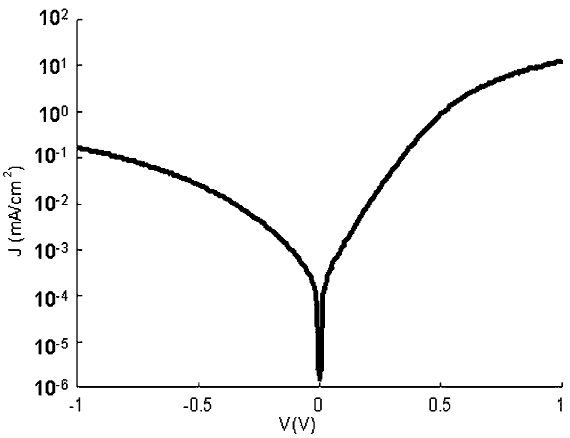

Fig. 6. Dark current density–voltage characteristics of drift dominated InP/GaP photodiodes.

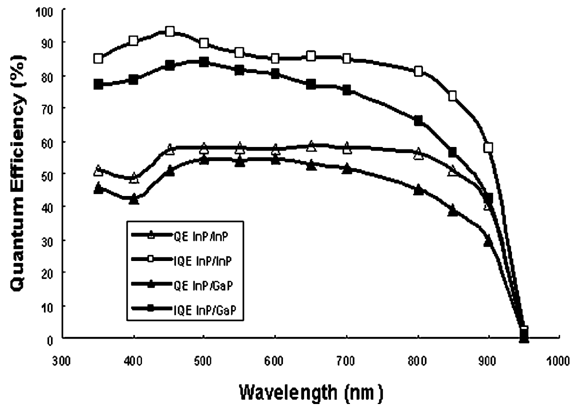

Fig. 7. Quantum efficiency as a function of photon wavelength for drift dominate InP/GaP photodiodes and InP/InP devices.

the UV-enhanced Si detector to measure the incident photon power and the HP4156B Semiconductor Parameter Analyzer to measure the photon generated current under 0 V bias. The results are shown in Fig. 7. The internal quantum efficiency is derived from the measured external efficiency and theoretical value of InP reflectivity as a function of wavelength. For comparison, the spectral response for our pervious InP on InP substrate devices is also shown in the figure. The results show that performance of the InP/GaP devices is almost as good as InP/InP devices, only about 10% drop in the UV and visible region. The spectral response in infrared has larger degradation due to the larger portion of the illumination that has been absorbed out of the active region and the trapping by defects and dislocations of many carriers generated. The results demonstrate that our drift dominated devices, of which electrical fields exist in the active region and carriers are collected by drift instead of diffusion, can greatly enhance the quantum efficiency even in the existence of defects. It is also worth to mention that we get larger than 70% internal quantum efficiency at 350 nm, which is just as expected since the surface band bending layer is very thin due to the very high surface doping concentration.

7. Conclusion

Our results to date indicate that drift dominated InP/GaP photodiodes have excellent spectral response especially in the UV and visible region where higher than 75% internal quantum efficiency and only about 10% degradation from InP on InP substrate devices are observed. Therefore, it demonstrates the robustness of the drift dominated devices even with the existence of dislocations and defects. This is because under large electrical fields, the photogenerated carriers are transported very rapidly and can reach the other side of the junction within several picoseconds to contribute to the overall photocurrent before being trapped by the defects. The drift dominated design will be very useful for InP/Si technology and application.

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