Photodiode characteristics and band alignment parameters of epitaxial Al$_{0.5}$Ga$_{0.5}$P

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Wide-bandgap semiconductor Al$_x$Ga$_{1-x}$P is a promising material candidate for low-noise photodiodes in blue/UV spectrum. Photodiodes were fabricated on Al$_{0.5}$Ga$_{0.5}$P epitaxial layer grown lattice matched on GaP substrate by molecular beam epitaxy. Although quantum efficiency is low for standard $p$-$i$-$n$ photodiode due to inadvertent photon absorption in the top $p$-layer, it can be significantly improved by opening a recessed window in the top $p$-layer or by using a Schottky junction photodiode structure. Al$_{0.5}$Ga$_{0.5}$P band alignment parameters can be extrapolated from the current-voltage characteristics of Al$_{0.1}$Ga$_{0.9}$P Schottky junctions. The bandgap of Al$_{0.5}$Ga$_{0.5}$P was measured to be 2.38 eV. © 2009 American Institute of Physics.
Ohmic contact for the n-layer was made with alloyed AuGe-Ni on the back side of the GaP substrate. Front metal contact was made with nonalloyed TiAu on heavily doped p++-GaP layer. Three different photodiode structures were fabricated and characterized, as shown in the insets in Fig. 2. Structure (a) is a standard p-i-n photodiode, where a ring-shaped metal contact (TiAu) was deposited by e-beam evaporator on the top p++-GaP layer for device probing. Although this structure is simple for fabrication, its QE is degraded by absorption of photons and recombination of the generated electron-hole (e-h) pairs in the top p-layers. This QE loss is especially severe in short wavelength spectrum where the photon penetration depth is shallow and a large portion of photons is absorbed in the top GaP layer instead of in the active Al0.5Ga0.5P layer below. To reduce the QE loss, structure (b) employs a recessed window by etching part of the top p-layers in the center of the ring contact. Structure (c) is a Schottky junction photodiode, where the top p-layers were removed by etching. A very thin (~10 nm) metal layer was deposited directly on top of undoped Al0.5Ga0.5P to form a metal-semiconductor junction.

Figure 2 shows the external QE of the three photodiode structures in the wavelength range of 650–400 nm. The measurement equipment limited the shortest wavelength to 400 nm. The photodiodes were reverse biased at ~10 V. Because the undoped i-layer is fully depleted, the measured QE only varies slightly with reverse bias voltage. The long-wavelength cutoff for all devices is between 500 and 550 nm, corresponding to a bandgap in the range of 2.25–2.48 eV. It will be shown later that the bandgap of the epilayer Al0.5Ga0.5P measured to be ~2.38 eV. QE increases quickly with decreasing wavelength due to higher absorption coefficient at shorter wavelength. With further decrease in wavelength, QE may start to decrease due to increasing surface absorption/recombination and result in a peak in the spectral response, which was not observed in this measurement due to limited wavelength range. The QE of the standard p-i-n photodiode, i.e., structure (a), is quite low because of photon absorption in the top p-layers. The absorption coefficient of GaP at photon energy of 3.1 eV (i.e., λ =400 nm) is α=8.63×10^4 cm^-1, corresponding to photon penetration depth of d=1/α=116 nm in GaP. Therefore, more than half of the incident photons were absorbed in the top 50 nm thick p++-GaP layer and 40 nm thick composition-grading p+-layer, where recombination rate is high due to extremely heavy doping and surface states. Consequently, most e-h pairs generated by these photons recombine without contributing to electrical response. QE can be significantly improved by etching a recessed window in the top p-layers to reduce photon absorption there, as shown by structure (b). The QE of structure (b) is more than twice higher than that of structure (a). Further improvement of QE was achieved in Schottky junction photodiode (c). In structure (c), high electric field exists in the Al0.5Ga0.5P layer underneath the metal-semiconductor junction. The field separates the e-h pairs generated by photons passing through the metal contact, which reduces the probability of recombination and improves QE. By making the metal contact sufficiently thin, the photon absorption in the metal layer can be minimized.

The external QE of Schottky junction photodiode on epitaxial Al0.5Ga0.5P reaches ~34%. A ring-shaped thin metal contact was also made for Schottky junction photodiode to increase photon absorption, and the QE was measured to be >45%. However, the electrical field in the i-layer is not in the vertical direction due to the ring-shaped top contact, which may affect the carrier transport and the photodiode response speed. In comparison with GaP-based photodiode, the spectral response of Al0.5Ga0.5P photodiode is shifted to shorter wavelength due to wider bandgap of Al0.5Ga0.5P. Further improvement on the efficiency of Al1Ga1-P photodiodes may be achieved by reducing surface reflection to maximize photon absorption, by improving the quality of the epitaxial material to reduce recombination, or by optimizing the photodiode structure, etc. Photodiodes based on Al0.75Ga0.25P were also fabricated and characterized. They demonstrated spectral response very similar to that of Al0.5Ga0.5P photodiodes, with slightly higher efficiency. The bandgap difference between Al0.75Ga0.25P and Al0.5Ga0.5P is expected to be ~0.05 eV, corresponding to the long-wavelength cutoff difference of ~10 nm, which is too small to be observed in this measurement.

The long-wavelength cutoff in the spectral response in Fig. 2 provides a rough range for the bandgap of Al0.5Ga0.5P. This bandgap can be more accurately determined by measuring the barrier heights of Schottky junctions on n- and p-type substrates, Φn and Φp, respectively. The bandgap can be calculated from $E_G=\Phi_n+\Phi_p$. In this experiment, two MBE samples were prepared, with 0.1 µm thick undoped Al0.5Ga0.5P layers grown on n+ and p++ substrates. Au contact was deposited by e-beam evaporator on these samples to form m-n and m-p Schottky junctions. Devices were isolated by etching through the Al0.5Ga0.5P layers into the substrates. The current-voltage (I-V) characteristics of these junctions were measured using semiconductor parameter analyzer HP 4156. Figure 3 shows the forward bias I-V characteristics of Schottky junctions on n- and p-type substrates, both demonstrating linear behavior over more than four orders of magnitude on semilogarithm scale. The ideality fac-
The accuracy of the metal work function. Compared to the offsets. However, the reliability of the estimation depends on the metal work function. The bandgap of Al$_{0.5}$Ga$_{0.5}$P was calculated to be 2.37 eV in literature. It corresponds to a cutoff wavelength of 520 nm in spectral response, consistent with the theory, the Schottky junction barrier heights were estimated to be 1.46 eV and 0.92 eV, respectively. There- is a type-II heterojunction with staggered gaps as suggested in Ref. 12.

In summary, photodiodes were fabricated on Al$_{1-x}$Ga$_x$P and the measured QE is promising for photodetector applications in blue/UV spectrum. QE can be significantly improved by optimizing the photodiode structures to reduce inadvertent surface photon absorption and carrier recombination. The bandgap of Al$_{0.5}$Ga$_{0.5}$P was measured to be 2.38 eV, based on the $I$-$V$ characteristics of Schottky junctions. The measured Au/Al$_{0.5}$Ga$_{0.5}$P band edge alignment parameters are consistent with reported results in literature.

Using the Au/Al$_{0.5}$Ga$_{0.5}$P band edge alignment parameters, it is possible to estimate the electron affinity of Al$_{0.5}$Ga$_{0.5}$P and to further determine Al$_{0.5}$Ga$_{0.5}$P/GaP band offsets. However, the reliability of the estimation depends on the accuracy of the metal work function. Compared to the Au/Al$_{1-x}$Ga$_x$P band edge alignment parameters in Ref. 12, our results were larger by 0.08–0.10 eV, which is within the 0.10 eV error margin in this reference. Although it is difficult to accurately estimate Al$_{0.5}$Ga$_{0.5}$P/GaP band offsets here, it is likely that Al$_{0.5}$Ga$_{0.5}$P/GaP is a type-II heterojunction with staggered gaps as suggested in Ref. 12.

![Diagram](image)

**FIG. 3.** The forward bias $I$-$V$ characteristics of Au/Al$_{0.5}$Ga$_{0.5}$P Schottky diodes made on $n$-type (left panel) and $p$-type (right panel) substrates. From the $I$-$V$ curves, the Schottky barrier heights were calculated to be 1.46 and 0.92 eV for junctions on $n$- and $p$-type substrates, respectively. The inset shows the Au/Al$_{0.5}$Ga$_{0.5}$P band edge alignment diagram calculated from the $I$-$V$ characteristics.

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