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Michael R. Melloch
Purdue University, melloch@purdue.edu

C. P. McMahon
Purdue University

Mark S. Lundstrom
Purdue University, lundstro@purdue.edu

J. A. Cooper Jr.
Purdue University

Q D. Qian
Purdue University

See next page for additional authors

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Authors
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Bias-dependent photoresponse of p^+in GaAs/AlAs/GaAs diodes

M. R. Melloch, C. P. McMahon, M. S. Lundstrom, J. A. Cooper, Jr., Q-D. Qian, and S. Bandyopadhyay
School of Electrical Engineering, Purdue University, West Lafayette, Indiana 47907

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We report photocollection efficiency measurements of p^+in GaAs/AlAs/GaAs diodes fabricated on films grown by molecular beam epitaxy. Both the zero-bias and bias-dependent photocollection characteristics can be explained by assuming that the band discontinuity between AlAs and GaAs is mostly accommodated in the valence band.

Due to the important device applications of GaAs and $Al_xGa_{1-x}As$, there has been much activity in recent years to determine the band alignment of this heterojunction.[1–10] It is presently accepted that the Γ GaAs to Γ AlGaAs conduction-band discontinuity is between 0.6 and 0.65 of the direct band-gap difference. Recent workers have shown that Γ GaAs to X AlGaAs (in the indirect alloy) conduction-band discontinuity is significantly below 60% of the indirect band-gap difference.[6,8,10] From photosensitive capacitance-voltage measurements and internal quantum efficiency measurements of p^+in and n^+ip GaAs/AlAs/GaAs photodiodes, we have seen qualitative evidence that the band discontinuity between AlAs and GaAs is mostly accommodated in the valence band;[11,12] this is in agreement with recent reports of other investigators.[6,8,10] In this letter we report bias-dependent photoresponse measurements of p^+in photodiodes. The measurements clearly demonstrate that the band discontinuity is largely accommodated in the valence band.

The device, whose structure is shown in Fig. 1, uses films grown by molecular beam eptiaxy (MBE) in a Perkin–Elmer PHI 400 MBE system. The starting substrates were (100) cut and silicon doped at 1.5×10^{18} cm^{-3}. The GaAs buffer layer was grown at a substrate temperature of 600 °C and doped with silicon to 1.9×10^{16} cm^{-3}. The 4210-Å-thick undoped AlAs layer was grown at a substrate temperature of 700 °C. The top GaAs layer was grown at a substrate temperature of 600 °C and doped with beryllium to 1×10^{18} cm^{-3}. (The doping densities were determined by capacitance-voltage profiling.) Devices of dimension 300 μm by 300 μm were defined by photolithography and subsequent wet etching. Ohmic contacts of dimension 100 μm × 100 μm were then made to the top GaAs layer.

The relative photocollection efficiency is shown in Fig. 2 for the p^+in diode whose dimensions are shown in Fig. 1. The Fig. 2 data were taken at a temperature of 300 K and relative photocollection efficiencies are shown for various applied reverse bias. For our device dimensions, the absorption of the light will shift from the n GaAs buffer layer to the top p^+ GaAs layer as the wavelength decreases. From the Fig. 2 zero-bias photocollection efficiency one sees that the minority-carrier holes in the n GaAs buffer layer are not as efficiently collected as minority-carrier electrons in the p^+ GaAs top layer. This suggests a larger band-gap discontinuity in the valence band than in the Γ GaAs to X AlAs conduction band. As the wavelength of the light decreases past 500 nm, the photocollection efficiency begins to decrease. This decrease is due to surface recombination as more and more carriers are being generated near the surface. As the wavelength decreases below 420 nm, there is an initial increase in the photocollection. This increase is due to direct band-to-band generation in the AlAs layer. Also seen in the Fig. 2 data is that as the p^+in diode is reverse biased, the

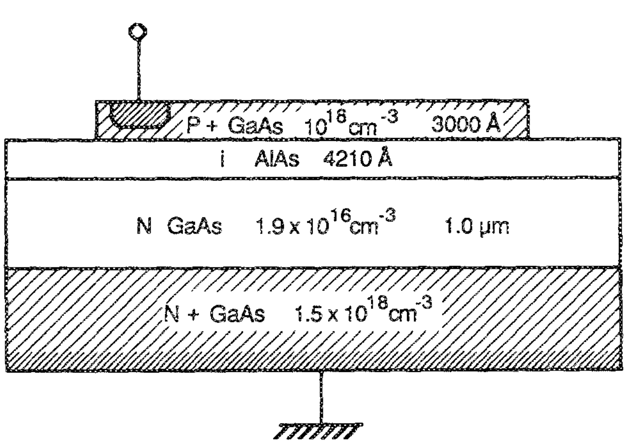

FIG. 1. p^+in GaAs/AlAs/GaAs device structure.

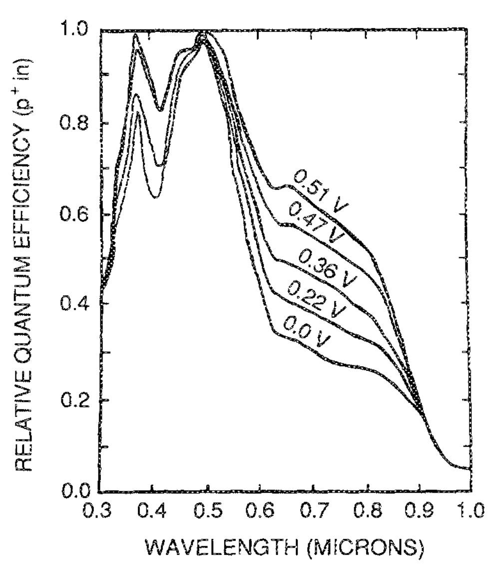

FIG. 2. Relative photocollection efficiency for the p^+in GaAs/AlAs/GaAs photodiode (whose dimensions are shown in Fig. 1) with external bias as a parameter.

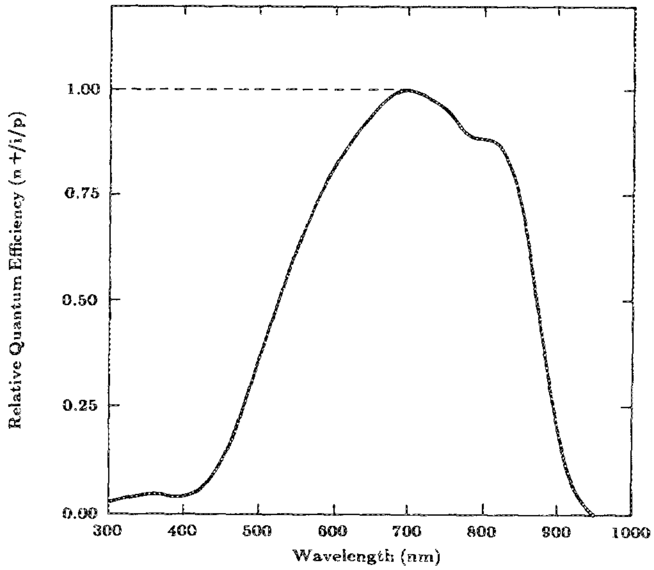

FIG. 3. Relative photocollection efficiency for an n^+ip GaAs/AlAs/GaAs photodiode. The top n^+ GaAs layer was 3000 Å thick and the AlAs layer was 2800 Å thick.

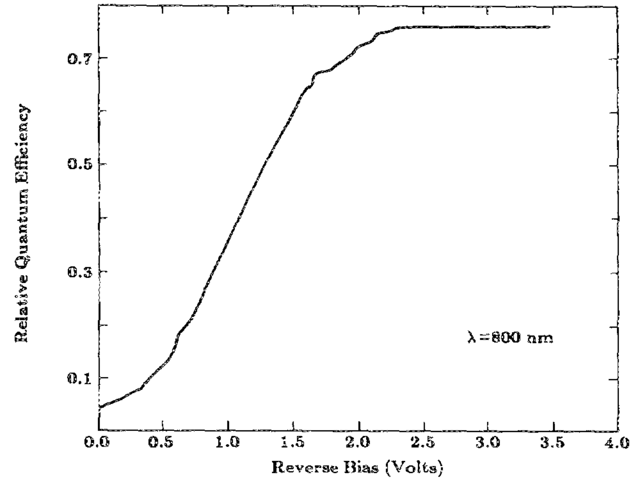

FIG. 4. Relative photocollection efficiency at a wavelength of 800 nm as a function of reverse bias of the p^+in photodiode.

collection of minority-carrier holes in the n GaAs buffer layer increases relative to the minority-carrier electrons in the p^+ GaAs top layer.

A complementary device, n^+ip GaAs/AlAs/GaAs diode, was also fabricated and its zero-bias relative photocollection efficiency is shown in Fig. 3. Again for this device the absorption of the light will shift from the p GaAs buffer layer to the top n^+ GaAs layer as the wavelength decreases. From the Fig. 3 relative photocollection efficiency one sees that minority-carrier holes in the top n^+ GaAs layer are not as efficiently collected as minority-carrier electrons in the p GaAs buffer layer which also suggests that the valence-band discontinuity is much larger than the conduction-band discontinuity. (Note that the sharp decrease in photocollection efficiency for wavelengths shorter than 650 nm is not due to surface recombination which does not become significant unless $\lambda < 500$ nm; the sharp decrease is due to poor photocollection efficiency for holes.)

The photocollection efficiency at a wavelength of 800 nm for the p^+in structure depicted in Fig. 1 is shown as a function of reverse bias in Fig. 4; the measurement was made at a temperature of 300 K. At 800 nm the depth required to absorb 90% of the light in our structure is 1.73 μm.[13] Therefore, at 800 nm a large portion of the light is absorbed in the n GaAs buffer region. The data in Fig. 4 can be explained with the aid of Fig. 5. At zero bias there is a barrier to holes between the AlAs and n GaAs buffer region as shown in Fig. 5(a). As the diode is reverse biased the barrier will decrease, increasing the photocollection efficiency. At a large enough bias the barrier will be removed, as shown in Fig. 5(b), and the photocollection efficiency will saturate. One would expect that before the barrier is completely removed [as depicted in Fig. 5(b)] that the photocollection current would saturate when the holes are able to tunnel through the remaining potential barrier. An analysis based on a numerical technique for solving the Schrödinger equation[14] shows that this tunneling can lower the effective barrier by a maximum of 10 meV.

In summary, we have measured the relative photocollection efficiency of p^+in and n^+ip GaAs/AlAs/GaAs photodiodes. The photoresponses can be explained based on the band discontinuity between AlAs and GaAs being mostly accommodated in the valence band. The effect of external

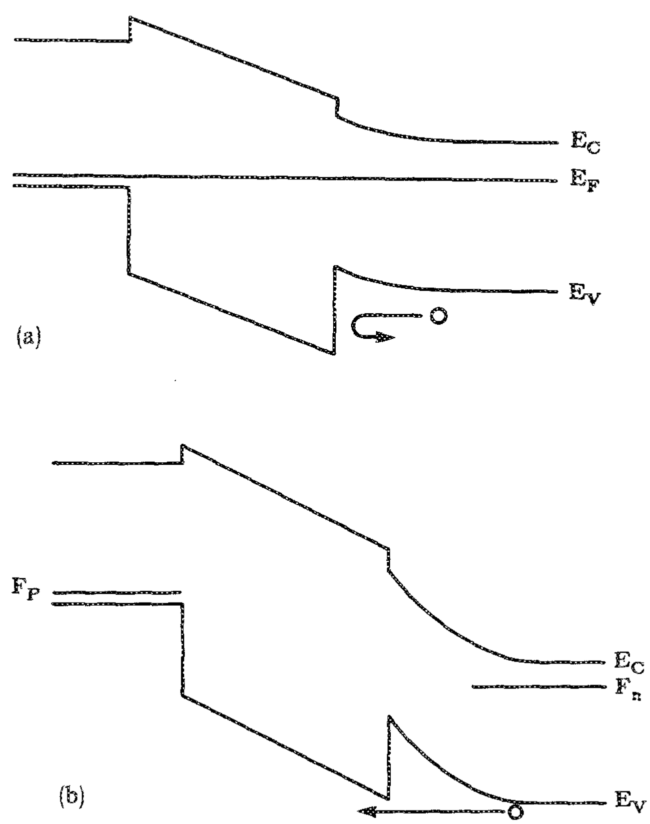

FIG. 5. Energy-band diagrams of the p^+in GaAs/AlAs/GaAs photodiode: (a) zero-bias condition; (b) biased to where the valence-band discontinuity is equal to the band bending in the n GaAs buffer region.

bias on the photoresponse of the p^+in GaAs/AlAs/GaAs diode was also reported.

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