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GaAsBi: An Alternative to InGaAs Based Multiple Quantum Well Photovoltaics

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***Abstract* — A series of GaAsBi/GaAs multiple quantum well p-i-n diodes are characterized using IV, photocurrent and illuminated IV measurements. The results are compared to an InGaAs/GaAsP multiple quantum well control device of a design that has demonstrated excellent performance in triple junction photovoltaics. The extended absorption of the GaAsBi/GaAs devices, compared to that of the InGaAs/GaAsP device, suggests that GaAsBi/GaAs could present a viable alternative to InGaAs/GaAsP for quad junction photovoltaics.**

***Index Terms* — bismuth compounds, gallium arsenide, quantum well devices, photovoltaic cells.**

I. Introduction

Dilute bismides are emerging as a class of material systems with many potential applications. Over the past 3 years, there have been significant results from bismides for detector [1], laser [2] and spintronic [3] applications.

It has been suggested that bismide based alloys could provide a candidate for the ~1 eV junction required in quad-junction solar cells [4]-[5]. Strain relaxation prevents the use of a simple bulk GaAsBi junction; it will be necessary to balance the compressive strain in such a junction on Ge, either through alloying with a tensile material such as B, N or P, or by growing the GaAsBi as part of a strain balanced multiple quantum well (MQW) junction [6]. Before analyzing strain balanced structures, however, it is instructive to investigate the performance of the more simple, strained MQW system, GaAsBi/GaAs. In this report, the properties of GaAsBi/GaAs MQW diodes are reported. The results are compared to those from a well-optimized strain balanced InGaAs/GaAsP MQW device, which was developed for use in triple junction solar cells.

II. Experimental

A systematic series of GaAsBi/GaAs MQW p-i-n diodes was grown by molecular beam epitaxy (MBE). The growth and structural characterization of these devices has been reported elsewhere [7]-[8]. These diodes comprise an n-type GaAs buffer, a 200 nm n-type $Al_{0.3}Ga_{0.7}As$ cladding region, a 620 nm MQW i-region, a 600nm p-type $Al_{0.3}Ga_{0.7}As$ cladding region and a thin GaAs capping layer. The i-region thickness of the diodes was kept constant throughout the series and the number of nominally 8nm GaAsBi wells varied between 3 and 63. A diagram of the structures is shown in Fig. 1.

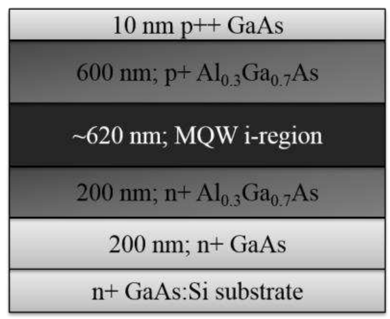

Fig. 1. The diode design used throughout this work.

TABLE I
Summary of Diode i-region Designs

Diode	Number of quantum wells	Barrier thickness (nm)
QW03	3	150
QW05	5	97
QW10	10	50
QW20	20	22
QW40	40	7.3
QW54	54	3.4
QW63	63	1.8

Table I describes the i-region of each diode.

A metal-organic vapor phase epitaxy grown p-i-n diode containing an i-region comprising 65 $In_{0.1}Ga_{0.9}As$ quantum wells of 8.3 nm width, strain balanced by 17.4 nm $GaAs_{0.911}P_{0.089}$ barriers, was used as a reference device for comparison.

The diodes were fabricated into mesa devices of radius 200 μm using standard photolithographic techniques.

The current voltage (IV) characteristics were measured in the dark and a tungsten bulb was used to illuminate the diodes for illuminated IV and photocurrent (PC) measurements. For the illuminated measurements, a GaAs filter was used to simulate operation in a quad junction solar cell.

III. Results

A. IV

The dark IV measurements from the GaAsBi diodes and the reference InGaAs/GaAsP diode are shown in Fig. 2.

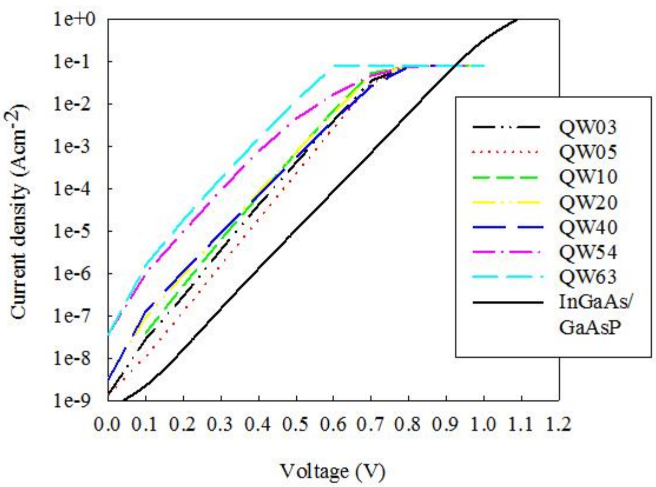

Fig. 2. Dark IV curves from the diodes in this work.

B. Photocurrent

The photocurrent from each of the devices is shown in Fig. 3.

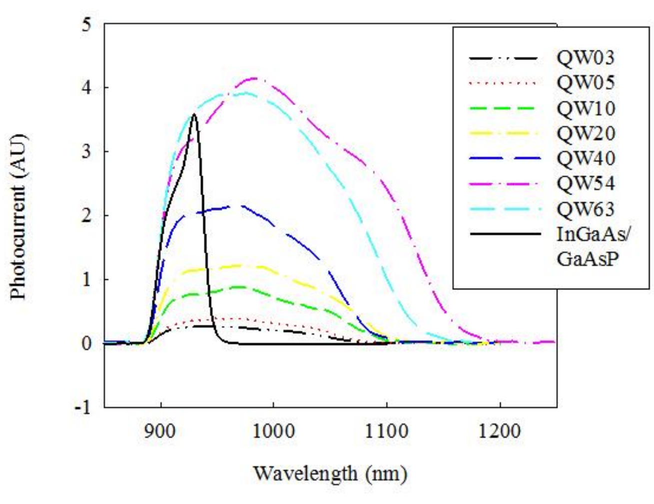

Fig. 3. Photocurrent from the diodes in this work, measured at 0 V bias under illumination from a tungsten bulb and under a GaAs filter.

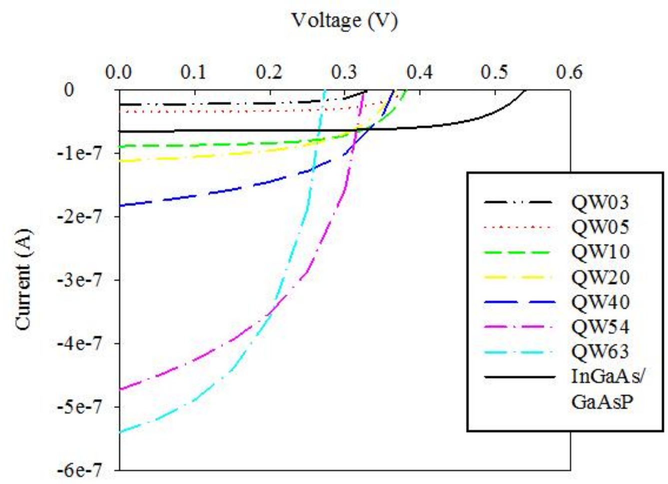

Fig. 4. Illuminated IV from the diodes in this work, measured under illumination from a tungsten bulb and under a GaAs filter.

The illuminated IV curves from each device are shown in Fig. 4.

IV. Analysis and Discussion

The dark IV results show that the InGaAs/GaAsP control device has a significantly lower dark current than any of the GaAsBi based devices. This is to be expected as InGaAs and GaAsP are very well understood materials and the InGaAs/GaAsP device in question was produced at the culmination of a significant optimization sequence for this device design. By contrast, the GaAsBi material system is not as well understood and the dark currents of GaAsBi based devices could be expected to be reduced as further progress is made in this area. The dark currents from InGaAs based MQW diodes were shown by Ekins-Daukes et al. to reduce by roughly one order of magnitude with the introduction of strain balancing [6], suggesting that the dark currents of the GaAsBi based devices may also be reduced by strain balancing.

All of the devices in this work demonstrate good rectifying behavior with ideality factors between 1 and 2; although, QW54 shows evidence of a high series resistance, the origin of which is not understood.

The dark currents of QW54 and QW63 are roughly an order of magnitude higher than those of the other samples in this series. This is likely due to strain relaxation, as indicated by previous work on the structural characterization of these devices [7]-[8].

The photocurrent measurements show that the GaAsBi devices absorb light to much longer wavelengths than the InGaAs/GaAsP device. Again, the 54 and 63 well devices show different characteristics to the other devices in the series. QW54 and QW63 absorb light to even longer wavelengths than the rest of the series and they have a higher peak photocurrent. It seems likely that this is again due to strain relaxation, specifically the reduction of the QW band gap due to the loss of compressive strain.

The InGaAs/GaAsP device demonstrates roughly twice the photocurrent of the 40 QW GaAsBi device up to ~930 nm. The absorption in the GaAsBi based devices could be expected to be improved by the introduction of strain balancing, allowing more QWs to be incorporated in the devices without strain relaxation.

The Illuminated IV measurements show that the InGaAs/GaAs device demonstrates the best open circuit voltage (V_{OC}). However, the GaAsBi devices with 10 or more QWs demonstrate a higher short circuit current (I_{SC}). In fact, the V_{OC} of the 40 QW diode is two thirds of that of the InGaAs/GaAsP device, while its I_{SC} is nearly three times as large. This leads to the V_{OC} I_{SC} product of the 40 QW GaAsBi/GaAs diode being nearly twice that of the InGaAs/GaAsP diode.

As these data were taken under illumination from a tungsten bulb, rather than a solar simulator, it is not possible to extract accurate fill factors from Fig. 4. and further work is required to characterize these devices under a calibrated solar spectrum.

Fig. 5 shows the photocurrent measured at 1000 nm at 0 V bias as a function of the number of wells in each device.

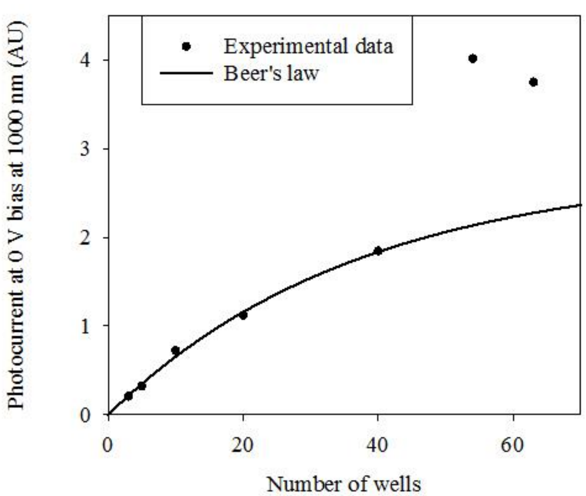

Fig. 5. Photocurrent from the diodes in this work at 1000 nm, at 0 V bias, fitted with Beer's law.

The fitting of the photocurrent data in Fig. 5. with Beer's law suggests that there is consistent absorption and extraction of carriers throughout the MQW series up to QW40. QW54 and QW63 are not well described by Beer's law, probably due to the strain relaxation mentioned earlier.

V. Conclusions

A series of strained GaAsBi/GaAs MQW p-i-n diodes were characterized using dark IV, photocurrent and illuminated IV measurements. The results were compared to those of a well optimized, strain balanced InGaAs/GaAsP MQW device. The InGaAs/GaAsP device shows significantly lower dark currents than the GaAsBi based devices, but this difference can probably be addressed by a deeper understanding of the growth of GaAsBi and by introducing strain balancing into GaAsBi based devices. The illuminated results show that the 40 QW GaAsBi/GaAs device has a V_{OC} I_{SC} product almost twice as large as that of the InGaAs/GaAsP device under illumination from a tungsten bulb. Further work is required to characterize these devices under a calibrated light source; however, the current results suggest that, with further optimization work, GaAsBi could compete with InGaAs as a ~1 eV junction for quad junction photovoltaics.

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