InAs-QDIP hybrid broadband infrared photodetector

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ABSTRACT

We demonstrated that an InAs photodiode and a Quantum Dot Infrared Photodiode can be bonded to produce a hybrid broadband infrared photodetector. When cooled to 77 K the InAs photodiode can be used to detect wavelengths from visible to a cutoff wavelength of 3 μm while the Quantum Dot Infrared Photodiode detects wavelengths from 3 to 12 μm. The dark current and spectral response were measured on reference devices and bonded devices. Both sets of devices show similar dark current and spectral response, suggesting that no significant degradation of the devices after the bonding process.

INTRODUCTION

The wavelength bands, 3-5μm and 8-12 μm, commonly referred to as the Midwave infrared (MWIR) and Longwave Infrared (LWIR) respectively, are important for a variety of infrared applications including infrared spectroscopy, radiation thermometry and thermal imaging. This is because the atmospheric attenuation is low and many chemicals of interest have unique infrared absorption spectrum in the MWIR and LWIR bands. Previous generations of infrared detectors have focused on the development of focal plane arrays and achieving high operating temperature. While these will continue to be important, development of future generation infrared detectors could add additional capabilities such as multispectral, polarization, internal gain and enhanced dynamic range.

One detector technology that is of interest to multispectral sensing is the Quantum Dot Infrared Photodiodes (QDIPs). QDIPs have peak responses that can be modified by applied bias [1]. When combined with a post processing algorithm, multispectral capability can be realized without using external wavelength selecting optical components (such as grating or filter) [2,3]. The absence of these optical components could reduce the cost and size of the infrared instruments, making QDIPs an attractive option.

In addition to multispectral sensing QDIPs can also offer a broad spectral response by varying the composition of the quantum dots. However, they are not suitable for detection of wavelengths below 3 μm, which is also of interest to gas sensing and spectroscopy measurements. With a bandgap of 0.35 eV at room temperature, InAs is an obvious detector option to extend the lower detection wavelength if it can be integrated with QDIPs. Besides having good detection efficiency at shorter infrared wavelengths, InAs has also been shown to have excellent impact ionization properties where high gain can be achieved with a gain independent excess noise factor below 2 [4]. In addition the gain-bandwidth product in InAs avalanche photodiodes is not limited [5] since only electrons can initiate impact ionization events, hence terminating the avalanche process within 2 carrier transit times.

This work aims to combine InAs which has excellent quantum efficiency in the shortwave infrared wavelengths and extremely low avalanche noise with the voltage tunable capability of QDIP in MWIR and LWIR wavelengths. We will adopt a wafer bonding technique which is now increasingly used to increase the detection spectrum of multi-junction solar cells [6] to boost the overall efficiency and to integrate components in photonic circuits [7]. The wafer bonding is also now offered as a commercial service, for example by AML [8]. Unlike epitaxially grown structures, this approach is not limited by lattice mismatch of the substrate and therefore has the potential to combine a wide range of photodetectors made from different materials.

EXPERIMENT

In this work an InAs p-i-n wafer and a QDIP n-i-n wafer were bonded. The InAs wafer was grown via Metal Organic Vapour Phase Epitaxy on a 2" p doped InAs substrate. It consists of a 2 µm n doped layer (Si, $1x10^{17}$ cm^{-3}), followed by a 6 µm intrinsic layer and then a 2 µm p doped layer (Be, $1x10^{18}$ cm^{-3}). A set of reference diodes were fabricated using our standard wet etching recipes [9] of a 1:1:1 (phosphoric acid: hydrogen peroxide: de-ionized water) etch, followed by a finishing etch of 1:8:80 (sulfuric acid: hydrogen peroxide: de-ionized water), to define the mesa diodes with radii between for 25 to 200 µm. The QDIP wafer was grown via Molecular Beam Epitaxy (MBE) on a semi-insulating GaAs substrate and consisted of 2 µm n+ GaAs layer, followed by 20 periods of a dot-in-a-well design and a 0.2 µm n+ GaAs layer. The dot-in-a-well structure consists of 50 nm $Al_{0.1}Ga_{0.9}As$, 4 nm GaAs, 1 nm $In_{0.15}Ga_{0.85}As$, 2 monolayers of InAs, 1 nm $In_{0.15}Ga_{0.85}As$, 6.85 nm of GaAs and 50 nm $Al_{0.1}Ga_{0.9}As$. A set of reference QDIP diodes were fabricated using the same 1:1:1 etchant as for the InAs wafer.

This wafer bonding process is illustrated in figure 1. First the thickness of the InAs substrate was reduced. This was achieved by mounting the sample on a metal block and mechanically thinned using a Logitech LP50 lapping and polishing system to a thickness of approximately 100 µm. The sample was then transferred onto a glass slide, remaining substrate side up and placed in a universal wet etchant solution (Hydrobromic Acid : Acetic Acid : Potassium Dichromate in a ratio of 1:1:1) to etch the sample thickness to less than 50 µm. To bond the wafers a layer of SU8 was spun onto the QDIP wafer mounted on a glass slide. The QDIP sample was placed on a hot plate at 95 ^{o}C and the InAs wafer was then placed, substrate side down, onto the SU8 (with the glass slide still covering the epi-side). The wafers were then lightly pushed together and left to bake for ~ 1 hour, the sample was then exposed to UV light for 240 seconds and placed in a developer solution before being baked again on a hot plate at 95 ^{o}C for a further hour. The glass slide was then removed by placing the sample in hot n-butyl.

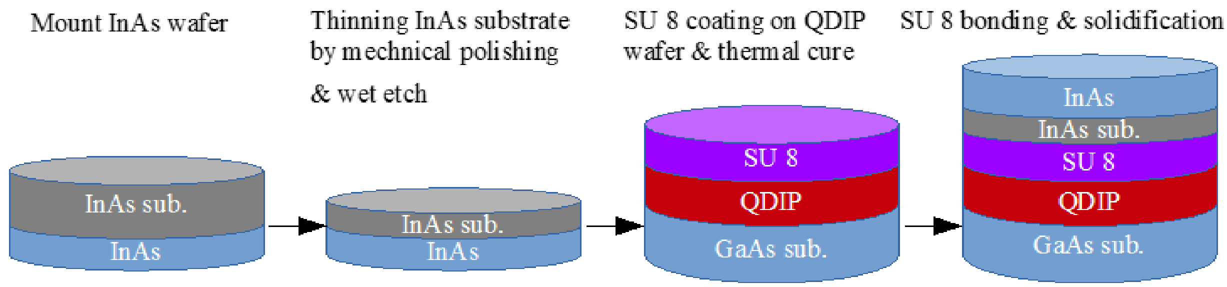

Figure 1: - wafer bonding process

The resultant bonded wafer was then processed into two junction mesa diodes of varying sizes, with top junction sizes of 1mm×1mm (large), 0.5mm×1 mm (medium), and 0.21 mm×0.235 mm (small). The junctions were defined via standard photolithography and with the use of the same etchants as for the standalone reference wafers described above. The SU8 layer was etched using a Reactive Ion Etch (RIE) comprising of O_2 and SF_6 [10]. Ti-Au (20/200 nm) was used for the top InAs contact while InGeAu (10/200 nm) was used for the bottom InAs contact and both contacts on the QDIP wafer.

Figure 2, shows a schematic diagram of the bonded structure along with SEM images of the bonded region and the fabricated mesa diodes. From the SEM images in figure 2 it can be seen that the SU8 has a thickness of approximately 12.4 µm. Both reference wafers and the final bonded wafer were mounted onto TO-5 headers for subsequent measurements. Spectral measurements for both the reference diodes and the bonded diodes were performed using a Fourier Transform IR spectrometer, while current-voltage characteristics were measured using a Keithley 236 Source Measurement Unit.

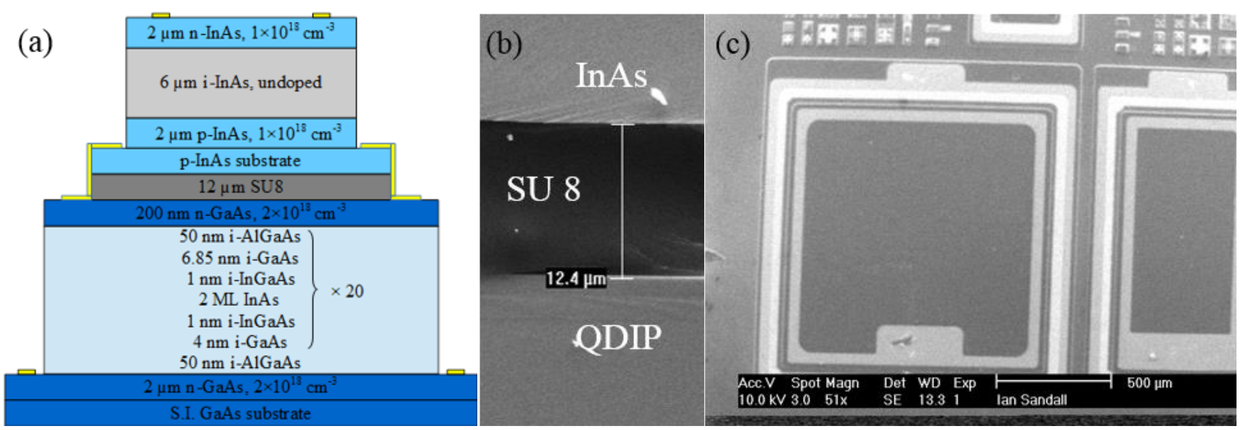

Figure 2: - (a) Cross section of the InAs and QDIP structures, (b) SEM image of bonded InAs-QDIP and (c) Top view of fabricated mesa diodes.

Due to the relatively high dark currents in QDIP diodes, it was necessary to cool the diodes to 77 K to allow for an accurate comparison of the device performance. Figure 3 shows the 77 K dark currents for both the InAs junction (3a) and the QDIP junction (3b), with the dashed lines showing data for the reference devices. It can clearly be seen in both cases that similar level of dark current is obtained from the bonded and un-bonded devices, showing that the bonding procedure deployed here has not caused significant degradation to the devices. The level of dark current in the bonded InAs remains below 1 $mAcm^{-2}$ at reverse bias of up to 10 V.

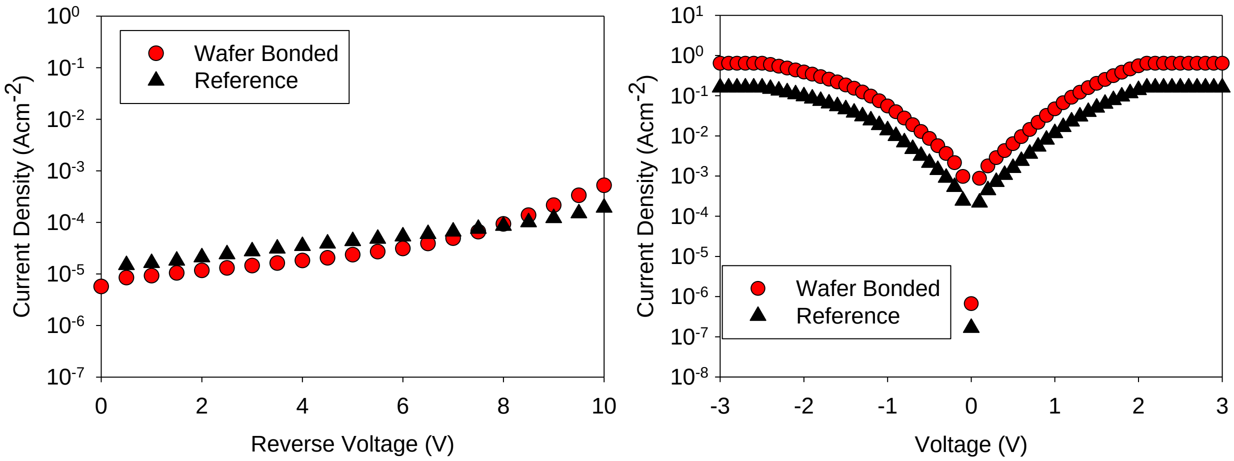

Figure 3: - Dark current density at 77 K measured on (a) InAs and (b) QDIP diodes.

To further assess this bonding technique we have also measured the absorption spectrum for both junctions and again compared them to that of standalone wafers. The absorption was measured by using an FTIR and commercial preamplifier to measure the photocurrent as a function of wavelength. Due to the high dark currents inherent in the QDIP these measurements were performed at 77 K. Figure 4a compares the spectral response from the InAs at -0.2V and QDIPs and –V from the bonded and reference devices respectively. Due to the differing sizes and geometries of the mesas for the reference and bonded devices the devices experience a differing collection efficiency of infrared light from the FTIR. As such we are not able to draw any conclusions regarding transmission through the SU8 layer or scattering at the interfaces. However it can be seen that the bottom QDIP based junction detects light over the same broad spectral region in the bonded device as the reference. To investigate if there is any variation in the transmission over this spectral region we have compared the normalized responses from before and after bonding in figure 4b. It can clearly be observed that the spectra responses are similar for the reference and bonded devices for both junctions.

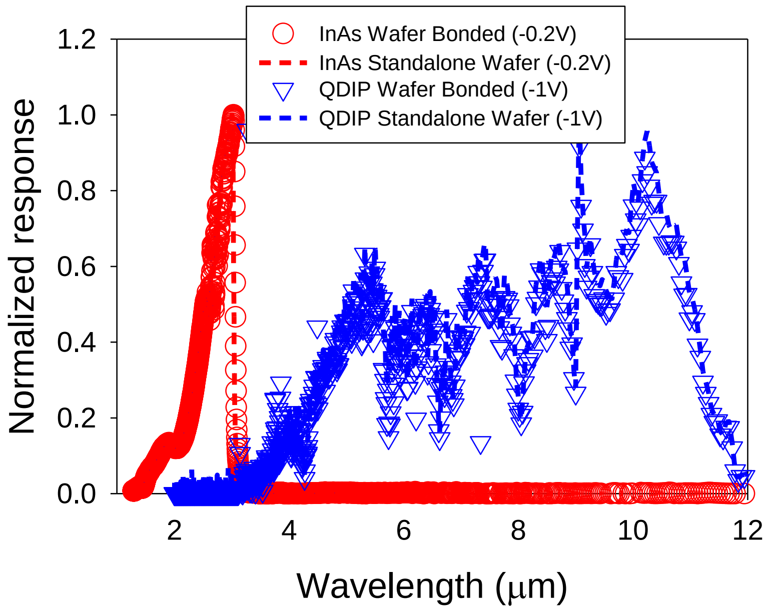

Figure 4: - Spectral response at 77 K measured from InAs diode biased at -0.2 V (circles) and QDIP diode biased at -1 V (triangles), the dashed lines are taken from reference standalone diodes

The bias dependent spectra of the QDIP is shown in figure 5. At -1 V, the normalized response is broadband with peaks at 5.5 and 10.4 μm, but increasing the bias to -2 V increases the response at 10.4 μm such that this becomes the dominant peak in the spectra response.

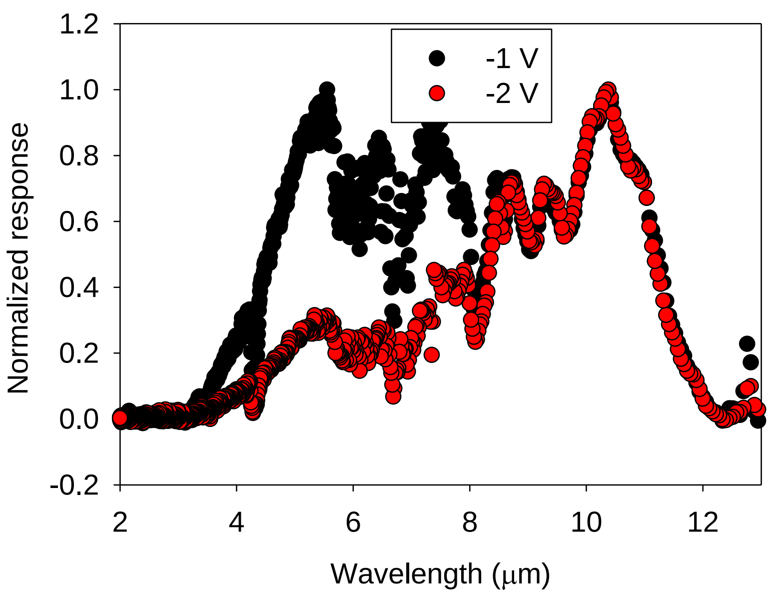

Figure 5: - Bias dependent spectral responses of QDIP at 77 K.

CONCLUSIONS

These results demonstrate that the two wafers can be successfully bonded together with an electrically insulating SU8 polymer, forming a two junction photodetector. Furthermore the similarity in the dark currents and spectra responses from InAs and QDIP devices on the reference and bonded devices indicate that the SU8 has sufficient thermal conductivity to allow the top junction to be cooled to 77 K and has sufficient transmission in the infrared wavelengths of interest. This was confirmed with a separate transmission measurement on a 10 μm think SU8, spun and baked under the same conditions as used for the wafer bonding. The SU8 absorption spectrum shows a broadly flat response over the wavelength range of interest with over 90% transmission.

The resultant spectra in figure 4 show that this two junction photodetector can be used as a hybrid broadband infrared photodetector operating from the visible to 3 μm (using InAs) and from MWIR to LWIR with a cutoff wavelength (at 50% relative to the peak response) of 11.2 μm (using QDIP). The QDIP also demonstrated some degree of bias dependent spectra response. The peak response can be tuned by the operating bias. In principle, this could potentially provide a versatile multispectral response when combined with a post processing algorithm to form an algorithmic spectrometer [2,3]. The InAs diode show low dark current density below 1 $mAcm^{-2}$, at a reverse bias of 10 V, demonstrating that it can be used in the avalanche mode since InAs demonstrated useful gain at bias below 10 V [4].

In conclusion we have demonstrated a dual band photodetector, achieved by bonding an InAs wafer to a QDIP wafer. The resultant detector is able to detect from the visible into the LWIR, with minimal degradation in dark current and spectral response. The InAs diode can be operated at bias range to achieve avalanche gain and the QDIP shows bias dependent spectra response after bonding process.

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