A Long-Wavelength, Annular $In_{0.53}Ga_{0.47}As$ p-i-n Photodetector

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Abstract—**We describe a novel, annular $In_{0.53}Ga_{0.47}As$ p-i-n photodiode sensitive to $\lambda = 1.7$ μm for use as a fiber tap or front-face laser monitor. The diode has a 150 μm diameter, straight-walled hole through the diode cross-section formed by photochemical etching. The hole is concentric with the 430 μm diameter mesa. A dark current of $I = 90$ nA at 5 V and a breakdown voltage of 33 V indicate that the hole formation process does not result in significant degradation of the device operating characteristics. Measurements of photoresponse as a function of position across the diode surface give further evidence that the hole does not effect overall device performance.**

RECENTLY, there has been considerable interest in optical data transmission systems operating in conjunction with low-loss, low-dispersion silica fibers. For detection of light over the wavelength region of $\lambda = 1.3$-1.6 μm, photodetectors [1-3] using $In_{0.53}Ga_{0.47}As$ as the absorbing material are being considered for system applications. This paper discusses a novel, annular $In_{0.53}Ga_{0.47}As$ p-i-n photodiode for use as a fiber tap, a front-face laser monitor, as a backscattered light detector (useful for reading optical-disc memories), and other lightwave applications. This detector consists of a 150 μm diameter, straight-walled cylindrical hole penetrating the entire wafer thickness and concentric with a 430 μm diameter mesa. The hole allows for transmission of light through the diode, while light peripherally incident on the annular mesa is detected. Thus, for example, when used as a fiber tap, it can be mounted within a connector joining two fibers. Light from one fiber is then focussed through the diode onto the adjoining fiber. However, light incident on the annular mesa active area is "tapped" and thus detected. The detector configuration somewhat resembles a recently reported GaAs detector [4]. In the latter device however, the active layers are not etched through, and hole formation was accomplished using conventional, isotropic etching techniques.

A schematic cross-section of the annular diode is shown in Fig. 1. The wafers are grown by liquid phase epitaxy [5] (LPE) on (100) n^+-InP substrates [6] doped to a net carrier concentration of $\sim 10^{18}$ cm^{-3}. Prior to growth, the wafers were etched for 3 min at room temperature in 3-H_2SO_4:1-H_2O_2:1-H_2O followed by multiple rinses with distilled and then dionized water. A 10 μm-thick unintentionally doped n-InP buffer layer is first grown, followed by 1 μm of unintentionally doped n-$In_{0.53}Ga_{0.47}As$ and a $1\frac{1}{2}$ μm-thick Zn-doped p^+-$In_{0.53}Ga_{0.47}As$ layer. The doping of the n-$In_{0.53}Ga_{0.47}As$ layer was 9×10^{15} cm^{-3} as determined using standard capacitance-voltage profiling techniques on the completed diodes. To process the wafers into diodes, the first step entailed electroplating the top contact ring metal (Au/Zn/Au) and the back contact metal (Au/Sn/Au) through photoresist masks on the p^+ and substrate surfaces, respectively. The back contact pattern consisted of 130 μm diameter holes in the metallization, concentric with the top contact ring. Next, 430 μm diameter mesas were defined using photolithography, and etched in 1-Br:100-CH_3OH. The straight-walled holes were then etched using a recently reported [7] photochemical technique. In this process the wafer is immersed in a 0.75 N-KF/0.75 N-HF solution and biased such that a depletion region is formed at the semiconductor surface. When the n-InP is irradiated with light whose energy is greater than the bandgap of 1.35 eV, minority carrier holes are photogenerated. These carriers participate in the oxidation of the semiconductor resulting in material removal from the illuminated regions. For our devices, the light is incident on the semiconductor surface through the 130 μm hole in the back contact metallization. In this manner, holes are etched whose taper is determined by diffraction and scattering of light from the bottom to the wall of the hole. Scanning electron micrographs made of the holes in our devices indicate a taper of $\sim 5°$ from the [100] direction. Etching proceeds until the hole extends to the p^+-$In_{0.53}Ga_{0.47}As$ layer. For most wafers of thickness ~ 175 μm, this process takes approximately 4 h. The high defect density in our wafers, however, enhanced minority carrier recombination which drastically slowed down the etch

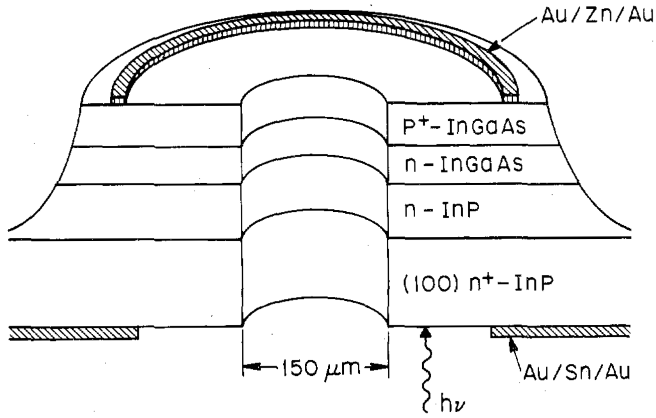

Fig. 1. Schematic cross-section of the annular p-i-n photodetector.

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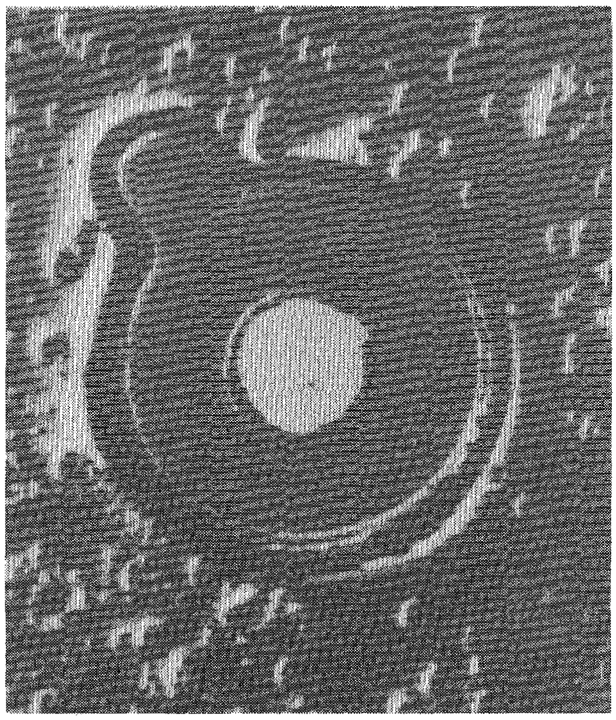
rate in some areas of the wafer. In other areas which were relatively free of defects, hole etching proceeded to rapid completion at the p^+-layer, with these holes slowly widening while those in the slow etch-rate area were completed. Thus, hole diameters as large as 150 μm were measured in areas of low dislocation density.

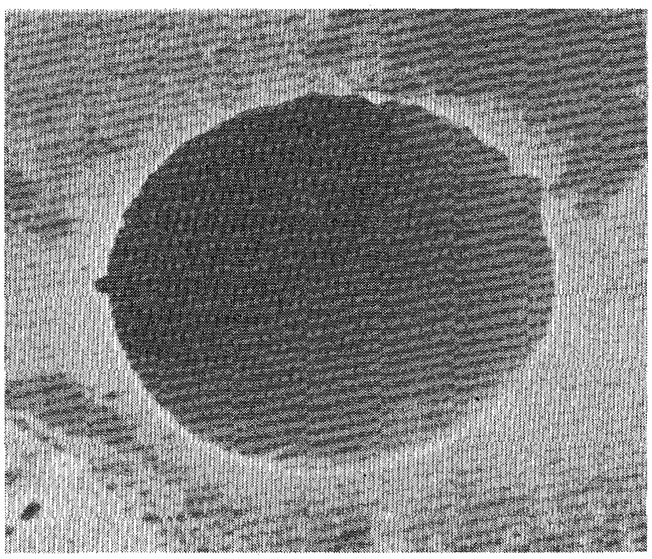
The hole was completed by etching from the mesa surface through a 125 μm diameter photolithographically defined hole mask using 1-Br:100-CH_3OH. This process results in annular diodes with total junction areas of $A = 1.5 \times 10^{-3}$ cm^2. Next, excess back metal used as a mask to the photochemical etch was removed out to a 500 μm diameter hole defined by photoresist applied to this surface. Finally, the metal contacts were alloyed and the mesas cleaned. A photograph of a completed mesa diode is shown in Fig. 2(a). The central hole is round and well defined with some jagged edges which indicate irregularities in the Au etch mask. Examination of the interior of the holes formed in a second, test wafer (Fig. 2(b)), indicates a very smooth surface with a few non-uniform features with dimensions of ~1 μm.

The reverse dark current-voltage (I_D-V) characteristics of the annular detector are shown in Fig. 3. At a bias of −5 V we find I_D = 90 nA, giving a current density (assuming currents flowing in the bulk of the mesa are dominant) of $J_D = 60$ μA/cm^2. This is comparable with results obtained for conventional small-area detectors made from this material system [1-3]. As the voltage is increased, I_D increases more rapidly than expected for generation-recombination or surface recombination currents frequently reported for $In_{0.53}Ga_{0.47}As$ diodes [8]. The rapid increase of I_D with voltage may be an indication of excess leakage due to surface shunt currents or due to numerous crystal defects apparent in this wafer. Finally, large increases in I_D with voltage at $V_B \gtrsim 33$ V (inset, Fig. 3) are characteristic of tunneling breakdown [8]. The breakdown voltage observed is normal for wafers doped to 9×10^{15} cm^{-3}. The observations of low dark current and normal breakdown voltage indicate that removal of large amounts of material from the p-n junction region does not significantly degrade device performance from that obtained in conventional small-area p-i-n diodes.

To further assess the degree of damage incurred during the hole etch, photoresponse to an 8 μm diameter light spot (λ = 6328 Å) was measured as a function of position across the mesa surface. Using this technique, recombination at defects which might cluster near the hole would be detected by a drop in photoresponse near the edge of the hole. The response profile is shown in Fig. 4. Features such as the mesa and hole edges, as well as the dip in response in the region of the metal contact ring are apparent. The enhanced response at the outer mesa edge is due to the high collection efficiency of carriers photogenerated directly within the depletion region as compared with the lower probability of collecting carriers generated at the mesa surface, ~$1\frac{1}{2}$ μm away from the depletion region edge. These latter carriers must diffuse a considerable distance prior to collection, and therefore can be lost to recombination. A comparison of the photoresponse profiles with microscopic measurements of diode geometry indicates that there are no regions of reduced sensitivity near the edges of the hole as might arise from crystal damage. This observation provides additional evidence that etching the hole using the photochemical technique results in no observable degradation in device performance. This is the first report where this etching technique has been used to expose the p-n junction in a device where low leakage current and uniform optical sensitivity are essential.



(a)



(b)

Fig. 2. (a) Top (mesa) surface of the annular detector. Illumination incident from the substrate side makes the hole appear lighter than mesa surface. (b) Micrograph of interior of hole etched in test wafer.

Next, the external quantum efficiency (η) versus wavelength for illumination on either the top or substrate diode surfaces was measured. Long-wavelength cutoffs observed at $\lambda = 1.7$ μm and $\lambda = 0.92$ μm are due to the $In_{0.53}Ga_{0.47}As$ and InP band edges, respectively. For top illumination, there is

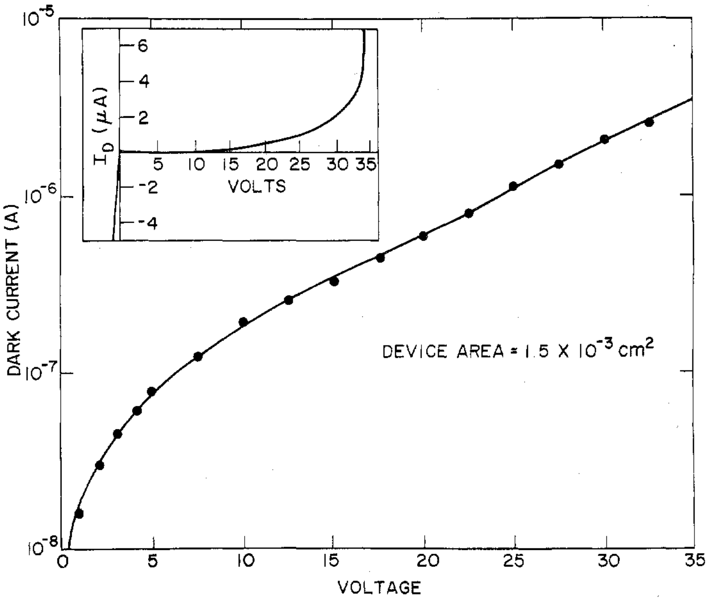


Fig. 3. Reverse dark current (I_D) v. voltage (V) for the annular detector. Inset: Forward and reverse current-voltage characteristics.

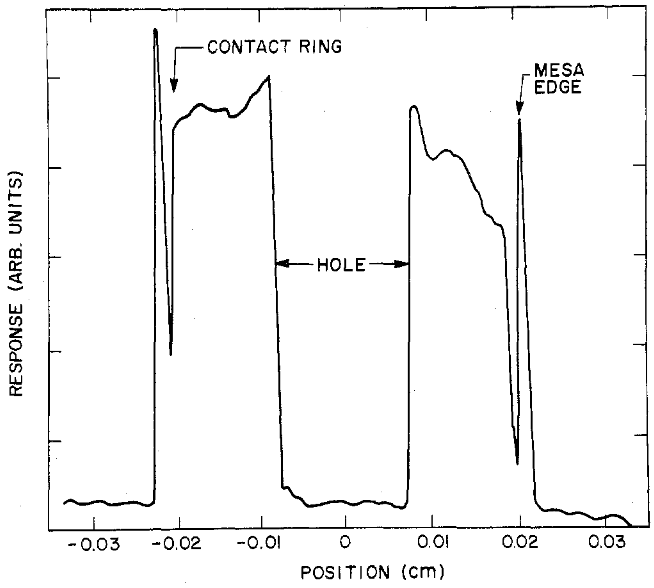


Fig. 4. Photoresponse profile of the annular detector measured using an 8 μm diameter, λ = 6328 Å light spot scanned across the mesa surface.

a decrease in efficiency from 49% at λ = 1.6 μm to η ~ 35% at λ = 0.95 μm due to absorption occurring closer to the top surface (and thus further from the depletion region edge) as photon energy is increased. Surface recombination may also reduce η as wavelength is decreased. In the case of back illumination, the quantum efficiency increases from η = 33% at λ = 1.65 μm to η = 67% at λ = 1.05 μm. This behavior, opposite to that observed for the front-illuminated diode, is probably due, in part, to free carrier absorption in the substrate. The external efficiency at λ = 1.3 μm for back-illuminated diodes is η = 52.8%. Efficiencies as high as 70% are expected for diodes of this type without anti-reflection coatings for n-$In_{0.53}Ga_{0.47}As$ layers ~2 μm thick. Finally, at –5 V the $In_{0.53}Ga_{0.47}As$ layer is completely depleted, giving a total device capacitance of 17.5 pF.

In conclusion, we have fabricated annular $In_{0.53}Ga_{0.47}As$ p-i-n photodetector diodes using a recently reported photochemical etching technique whereby a 150 μm diameter, straight-walled hole was etched through the wafer. Analyses of dark current, breakdown voltage and photoresponse have been presented, and they indicate that no significant degradation in device performance is incurred in the hole-formation process. Diodes of this geometry have potential application in several aspects of lightware communications. Due to the applicability of the hole formation process to all III-V compounds, these structures need not be confined to the $In_{0.53}Ga_{0.47}As$/InP system.

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