# $In_{0.53}Ga_{0.47}As$ *p-i-n* photodiodes with transparent cadmium tin oxide contacts

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A new type of *p-i-n* $In_{0.53}Ga_{0.47}As$ photodiode having an optically transparent composite top electrode consisting of a thin semitransparent metal layer and a transparent cadmium tin oxide (CTO) layer was investigated. The composite functions as the *n* or *p* contact, an optical window, and an antireflection coating. The transparent contact also prevents shadowing of the active layer by the top electrode, thus allowing greater collection of incident light. Since the CTO contact is nonalloyed, interdiffusion into the *i*-region is not relevant avoiding an increased dark current. The photodiodes exhibited leakage currents of $\leqslant 8$ nA and some as low as 23 pA, with reverse breakdown voltages of $\geqslant 15$–17 V. Responsivity was measured using a 1.55 $\mu$m InGaAsP diode laser focused onto an unpassivated 60 $\mu$m diam *p-i-n* photodiode and was $\geqslant 0.41$ A/W. Photoresponse of the diodes to 3 ps pulses from a Nd:YLF laser ($\lambda = 1.047$ $\mu$m) was 169 and 86 ps for the 60 and 9 $\mu$m diodes, respectively. The maximum frequency response of the 9 $\mu$m diode is packaging limited, and is expected to have an intrinsic response time of 20–30 ps.

III-V compound semiconductor photodiodes are a key component in optical communications. With increased data rates, faster photodiodes are required. There are two fundamental limits to the speed of a photodiode, (i) the transit time ($t_r$) which is the time to sweep the photogenerated carriers across the *p-n* junction to be collected by the contact and (ii) the RC time constant, which is a time associated with the capacitance of the photodiode for the given diode dimensions. Typically the transit time is quite fast, on the order of 5–10 ps, while the RC time constant is usually the limiting factor. To reduce the RC time constant, the photodiode can be made progressively smaller, but there is a tradeoff, as the photodiode area shrinks, the active area to collect light diminishes which in turn significantly reduces the optical signal measured. Since the top of the photodiode needs to be contacted with an electrode, this metallization shadows an increasing fraction of the photodiode area as the device shrinks. Hence, performance is compromised for smaller photodiodes.

We have developed a new type of *p-i-n* $In_{0.53}Ga_{0.47}As$ photodiode with a transparent cadmium tin oxide (CTO) top electrode. The CTO is optically transparent ($>80\%$) with negligible absorption and a conductivity of $2\times10^3$ $\Omega^{-1}$ cm$^{-1}$ and a resistivity of $5\times10^{-4}$ $\Omega$ cm at room temperature. The CTO contact has the following advantages: (i) it functions as both the *n* or *p* contact, (ii) it acts as an optical window, (iii) it serves as an antireflection coating, (iv) it prevents shadowing of the active layer by the top electrode, thus allowing greater collection of incident light, and (v) since the CTO contact is nonalloyed, interdiffusion into the *i*-region is not a factor, which avoids an increased dark current.

Reactive magnetron sputtering of transparent conducting oxides has been studied by Lewin *et al.*[1] who investigated both indium tin oxide (ITO) and CTO. Golan *et al.*[2] studied GaAs diodes using ITO as one of the contacts, but never studied the properties as a photodiode. Zirngibl *et al.*[3] did study extensively the property of GaAs based photodiodes using ITO contacts, but that was at $\lambda\sim0.85$ $\mu$m. ITO is not appropriate at $\lambda\sim1.55$ $\mu$m, because its absorption increases significantly ($\sim60\%$) However, CTO is still transparent at longer wavelengths. We are the first to study *p-i-n* $In_{0.53}Ga_{0.47}As$ photodiodes using CTO contacts, and the first to add a thin layer of metal below the CTO for a photodiode to avoid the problems outlined below. The only other application of CTO was by Tu *et al.*[4] for use as the top electrode on a GaAs-based vertical cavity surface emitting laser.

The thin layer of metal, $\sim100$ Å of either Ag or In, serves three functions: (i) it acts as an intermediary layer which makes a better nonalloyed electrical (ohmic) contact to the semiconductor surface, (ii) it prevents oxidation of the semiconductor underneath the contact from the $O_2$ in the plasma during reactive magnetron sputtering of the CTO contact, and (iii) it prevents formation of a *p-n* junction between the top semiconductor layer and the CTO layer.

The device is first grown by molecular beam epitaxy (MBE). The MBE structure consists of a superlattice buffer on a semi-insulating InP substrate, a 0.5 $\mu$m $n^+$-$In_{0.52}Al_{0.48}As$ lower contact ($1.0\times10^{18}$ cm$^{-3}$), a 0.75 $\mu$m $i$-$In_{0.53}Ga_{0.47}As$ active region ($1.3\times10^{15}$ cm$^{-3}$, *n*-type) with 100 Å $i$-$In_{0.52}Al_{0.48}As$ setback layers to either side to prevent outdiffusion of the dopants into the active region, a 0.2 $\mu$m $p^{++}$-$In_{0.52}Al_{0.48}As$ upper contact ($1.0\times10^{18}$ cm$^{-3}$), and a 200 Å $p^+$-$In_{0.53}Ga_{0.47}As$ contact layer ($5.0\times10^{18}$ cm$^{-3}$). A schematic of the photodiode is also shown in Fig. 1. The device is fabricated by lithographically patterning the active photodiode area and etching wet chemically down to the lower doped layer. The wafer is then patterned with a successively larger diameter isolation mesa. The epilayer is then etched down to the semi-insulating InP substrate. The lower contact is then

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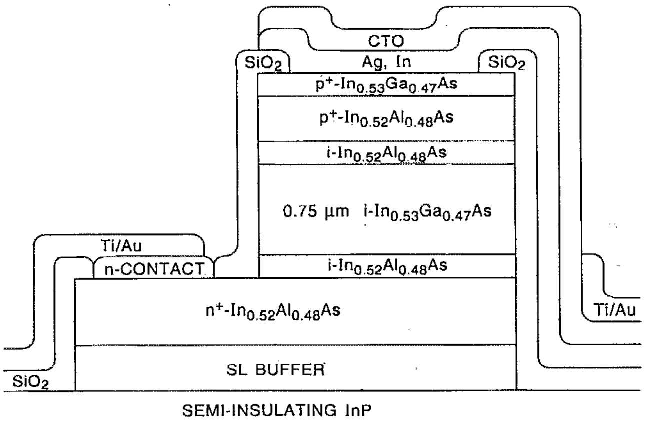

FIG. 1. Schematic cross-section of the fabricated *p-i-n* photodiode.

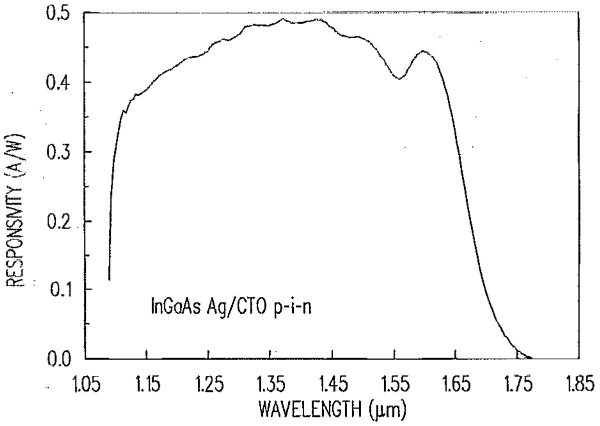

FIG. 3. Measured spectral responsivity of the $In_{0.53}Ga_{0.47}As$ *p-i-n* photodiode.

added by photolithography and liftoff. After alloying the lower contact, the sample is coated with $SiO_2$ by plasma enhanced chemical vapor deposition (PECVD). The $SiO_2$ is patterned lithographically to allow windows to be etched through it to reach the lower contact and the top of the active mesa. After etching through the $SiO_2$, the wafer is patterned for liftoff of the Ag/CTO contact atop the active mesa. First, the wafer is coated with ~100 Å of Ag or In by electron beam evaporation and then 3000 Å of CTO is deposited by reactive magnetron sputtering in argon which contains oxygen. After liftoff, the Ti/Au pads for probing are patterned and deposited. The Ti/Au pads extend over the mesas and onto the $SiO_2$, as shown in Fig. 1.

The *I-V* characteristics were measured and a typical *I-V* of a 60 $\mu$m diam photodiode is shown in Fig. 2. The photodiodes exhibited leakage currents of $\leqslant 8$ nA and some as low as 23 pA, and reverse breakdown voltages of $\geqslant 15$–17 V.

The zero bias microwave performance of 9 $\mu$m photodiodes was measured using a vector network analyzer and wide bandwidth coplanar waveguide probes. Measurements were made from 100 MHz to 40 GHz. The *S*-parameters measured were then used to obtain an equivalent circuit by optimizing the $\pi$-network. Optimizing the equivalent circuit yielded a device capacitance of 9.3 fF which is close to the calculated 11.6 fF for a 0.75 $\mu$m active region. The series resistance $R_s$ was around 34.7 Ω. The device is expected to be transit time limited, $t_r = 7.5$ ps, which corresponds to a $f_{3dB} = 85$ GHz.

Responsivity was measured using a 1.55 $\mu$m InGaAsP diode laser. Light was focused onto a 60 $\mu$m diam photodiode. A reverse bias of $-5$ V was applied through coaxial probes, and the photocurrent measured and compared to a

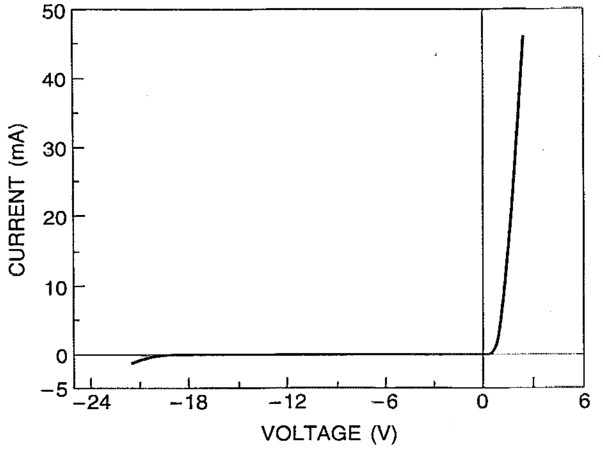

FIG. 2. *I-V* characteristics of the *p-i-n* photodiode.

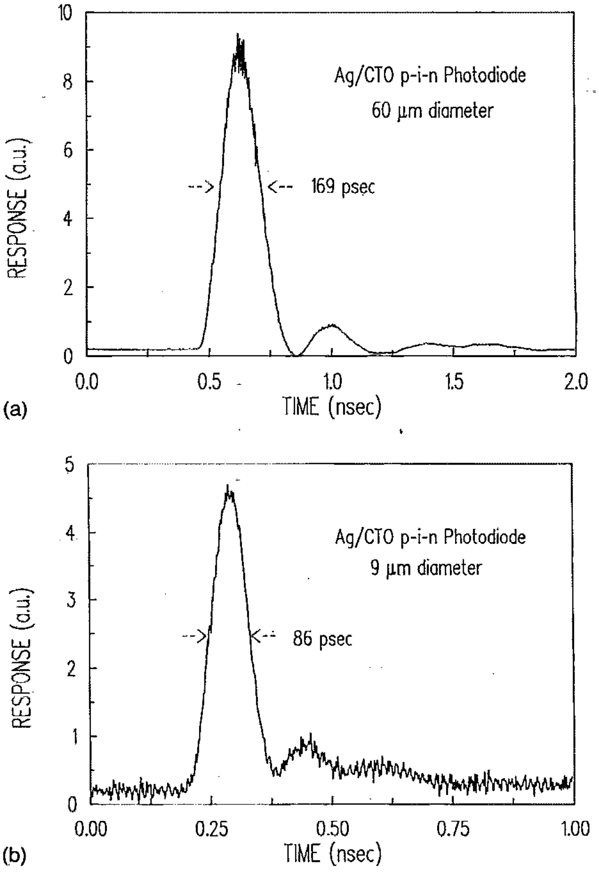

FIG. 4. Measured photoresponse to 3 ps pulses from a Nd:YLF laser ($\lambda = 1.047$ $\mu$m) for (a) a 60 $\mu$m diam and (b) 9 $\mu$m diam $In_{0.53}Ga_{0.47}As$ *p-i-n* photodiode.

calibrated Ge photoconductor. The responsivity of the *p-i-n* photodiode at 1.55 $\mu$m is at least 0.41 A/W.

The responsivity of the measured *p-i-n* $In_{0.53}Ga_{0.47}As$ photodiodes will be enhanced if proper choice of the CTO thickness is made. Reflections, not absorption, limited the responsivity of the measured data. The chosen thickness of 3000 Å CTO was later found to be half way between a perfect reflecting layer ($\lambda/2n$) and an antireflecting coating ($\lambda/1n$), when subsequent measurements revealed that the index of refraction is around 1.80–1.85 for reactively sputtered CTO. Estimates are that our chosen thickness reflected roughly 30% of the incident 1.55 $\mu$m light. Thus, our measured responsivity should be adjusted, and would result in about 0.5 A/W responsivity at 1.55 $\mu$m for our *p-i-n* $In_{0.53}Ga_{0.47}As$ photodiodes.

The spectral dependence on the response was also measured using a white light source and a monochrometer. The spectral response is shown in Fig. 3. The short wavelength cutoff is due to the long pass filter used to remove spectral harmonics created by the monochrometer.

Transmittance of the CTO was measured from 1 to 2 $\mu$m and shows a gradually decaying transmittance over the spectral range starting at ~97% at 1 $\mu$m and falling to ~85% at 1.55 $\mu$m. The transmittance of the In and Ag layers were also measured at the discrete wavelength of 1.55 $\mu$m and showed a 98.8% and 97.3% transmittance for ~100 Å of Ag and In, respectively.

The photoresponse of the photodiodes was measured by packaging the devices on a coplanar chip carrier and inserting it into a test fixture capable of handling up to 26.5 GHz. The photodiodes were then illuminated with 3 ps pulses from a self-starting intracavity-passive-mode locked Nd:YLF laser (1.047 $\mu$m) pumped with a Ti: sapphire CW laser.[5] The 60 $\mu$m diam photodiodes showed a full width half maximum (FWHM) of 169 ps, shown in Fig. 4(a), which is slightly higher than the 115 ps predicted. Parasitic capacitances of the top electrode and the lower *n*-type contact layer with $SiO_2$ sandwiched in between increased the RC time constant. The 9 $\mu$m photodiodes exhibited only a 86 ps FWHM response, shown in Fig. 4(b), which is drastically longer than the 20–30 ps expected. The smaller photodiode response time is limited by the packaging design and the bond wires. The microwave measurements using on-chip probing also confirm the low overall capacitance of the smaller 9 $\mu$m photodiode.

In summary, we have designed, fabricated and tested an $In_{0.53}Ga_{0.47}As$ photodiode which uses CTO as the upper contact. The CTO acts as a transparent conductor preventing shadowing of the active area.

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