$In_{0.53}Ga_{0.47}As$ metal-semiconductor-metal photodiodes with transparent cadmium tin oxide Schottky contacts

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(Received 18 April 1994; accepted for publication 4 August 1994)

A metal-semiconductor-metal (MSM) $In_{0.53}Ga_{0.47}As$ photodiode using a transparent cadmium tin oxide (CTO) layer for the interdigitated electrodes was investigated. The transparent contact prevents shadowing of the active layer by the electrodes, thus allowing greater collection of incident light. The barrier height (ϕ_{Bn}) of CTO on i-$In_{0.52}Al_{0.48}As$ was determined to be 0.47 eV, while the Ti/Au barrier height was 0.595 eV. The reduced barrier height for CTO is caused by tunneling through the sputter-damaged cap layer. Responsivity for 1.3 μm incident light was 0.49 and 0.28 A/W, respectively, for the CTO and Ti/Au MSM photodiodes. No antireflection (AR) coating was utilized over the bare semiconductor surface. The CTO MSM photodiode shows a factor of almost two improvement in responsivity over conventional Ti/Au MSM photodiodes. © *1994 American Institute of Physics.*

In the past few years metal-semiconductor-metal (MSM) photodiodes have become increasingly popular in the research field due to their high speed performance and ease of fabrication and integration. MSM photodiodes are comprised of back-to-back Schottky diodes by using an interdigitated electrode configuration on top of an active light collection region. The Schottky electrodes of the MSM photodiodes are essentially identical to the gate metalization of field effect transistors (FET). Therefore, it makes integration with FET-based amplifiers readily feasible.

The biggest drawback of MSM photodetectors is their intrinsic low responsivity. MSM detectors exhibit low responsivity mainly because the metalization for the electrodes shadows the active light collecting region. Shadowing can limit the incident light from reaching the active region of the MSM detector and prevent an ideal MSM from achieving responsivities of greater than 50% for equal electrode width and spacing.

Researchers have concentrated on making MSM photodiodes faster. But MSM photodiodes are inherently fast due to their low capacitance per unit area and are usually transit-time limited, not RC time constant limited. With electron beam lithography, the electrode width and spacing can be made with submicron dimensions which greatly improves the speed.[1] However, what needs to be addressed before MSM detectors can supplant or complement conventional p-i-n photodiodes is the issue of their low responsivity. A few researchers have investigated higher responsivity MSMs: Kim *et al.*[2] explored MSM photodiodes illuminated from the back side to avoid shadowing; Darling *et al.*[3] used an epitaxial n^+ layer as a transparent conductor; and both Zirngibl *et al.*[4] and Seo *et al.*[5] studied transparent indium tin oxide (ITO) conductors for electrodes. Back side illumination to avoid shadowing of the electrodes is impractical in many cases due to substrate absorption and complicates any possible monolithic integration. The epitaxial n^+-contact layer suffered from an excessive series resistance. And lastly, the research on transparent conductors as electrodes has dealt with ITO on GaAs. Cadmium tin oxide (CTO), which has greater transparency at long wavelengths, has been used as a transparent contact for p-i-n $In_{0.53}Ga_{0.47}As$ photodiodes as reported by Berger *et al.*[6] Berger *et al.*[6] also addressed the issue of the CTO-semiconductor interface by inserting a thin metal (Ag,In) to create an ohmic contact. We report here the first application of CTO transparent conductors to $In_{0.53}Ga_{0.47}As$ MSM photodiodes. The CTO contact has the following advantages; (i) it functions as the Schottky contact, (ii) it serves as an AR coating, and (iii) it prevents shadowing of the active layer by the top electrode, thus allowing greater collection of incident light.

Reactive magnetron sputtering of transparent conducting oxides has been studied by Lewin *et al.*[7] who investigated both ITO and CTO. ITO, normally utilized for $\lambda \leqslant 0.85$ μm on Si solar cells and sometimes GaAs photodiodes, is not appropriate at $\lambda \sim 1.55$ μm, because its absorption increases significantly ($\sim$50%). However, CTO is still transparent at longer wavelengths. Seo *et al.*[8] have reported recently an improvement in the transmission of ITO at 1.3 μm by adding a forming gas (H_2/N_2) mixture to the Ar sputtering gas. They used the modified ITO for InGaAs MSM photodiodes. However, the ITO with forming gas showed more than an order of magnitude degradation of the resistivity to a value of 1.5×10^{-2} $\Omega \cdot$cm at room temperature. CTO is optically transparent ($>$80%) in the region of interest for long wavelength communications with negligible absorption and a resistivity of 4×10^{-4} $\Omega \cdot$cm at room temperature.[7]

The MSM photodiode structure is grown by molecular beam epitaxy (MBE). The device consists of an InGaAs/InAlAs superlattice buffer on a semi-insulating InP substrate, a 0.75 μm i-$In_{0.53}Ga_{0.47}As$ active region ($\sim 1.3 \times 10^{15}$ cm^{-3}), and a 200 Å i-$In_{0.52}Al_{0.48}As$ Schottky barrier enhancement layer. The grown photodiode structure was characterized by photoluminescence (PL). The low-temperature (5.5 K) PL

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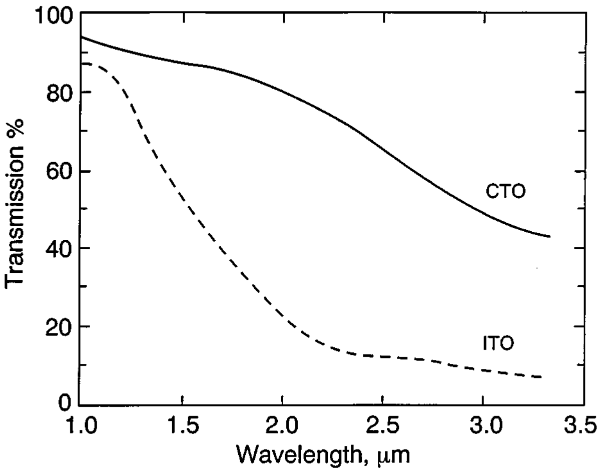

FIG. 1. Transmittance of 3000 Å CTO and ITO films reactively sputtered onto quartz for wavelengths from 1.0 to 3.3 μm.

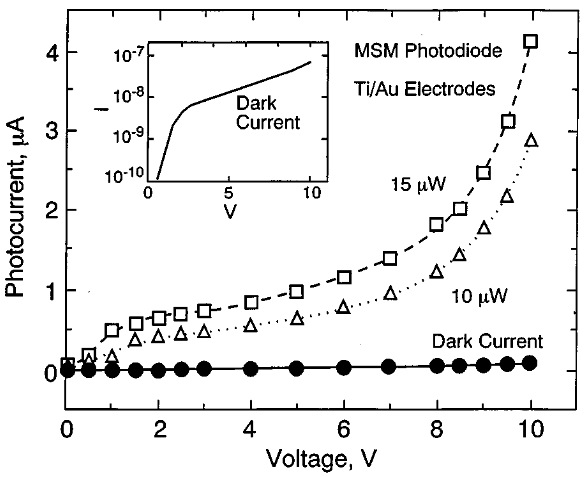

FIG. 2. Dark current and photocurrent under two arbitrary illuminations ($\lambda = 1.3$ μm from QTH lamp) for MSM photodiodes with 1 μm finger width and 2 μm spacing and active area of 75×75 μm^2 using Ti/Au electrodes.

showed a dominant peak at 0.795 eV (15 597 Å) with a full width at half-maximum (FWHM) of 7.1 meV.

The device is fabricated by conventional photolithography. The deposition of the optically transparent CTO layer was conducted using rf magnetron sputtering. The sputtering gas was a mixture of Ar and O_2. The resistivity of the CTO film strongly depends on the partial pressure of O_2. Minimum resistivity is obtained for an O_2 partial pressure of about $2\text{–}4 \times 10^{-2}$ Pa in 2–4 Pa Ar. The CTO thickness was about 2000 Å, which is close to the $\lambda/4$ thickness for an AR coating if previous values of index of refraction (2.0) are used.[7] The Ti/Au electrodes are evaporated in an e-beam evaporator. The Ti/Au thickness was 200 Å Ti and 1500 Å of Au. After liftoff of the MSM electrodes, thick Ti/Au pads for probing are also patterned for liftoff and deposited. The MSM photodiode is completely planar.

A comparison of the transmittance of reactively deposited ITO and CTO was made. Transmittance of 3000 Å ITO and CTO films deposited on quartz was measured using fourier transform infrared (FTIR) spectroscopy from 1 to 3.3 μm. The transmission curves of ITO and CTO are shown in Fig. 1. CTO shows a transmittance of over 85% between 1.3 and 1.55 μm. However, ITO shows ~50% over the same wavelengths. Clearly, CTO is a better choice for a transparent conductor at wavelengths suitable for long-haul optical fiber communications (1.3 $\mu m \leqslant \lambda \leqslant 1.55$ μm).

The barrier height (ϕ_B) of the CTO vs Ti/Au was investigated. An approximation of ϕ_B was obtained using the current-voltage (I-V) characteristics. The effective barrier height can be reduced due to tunneling through the barrier and image force lowering.[9] Sadwick *et al.*[10] reported the barrier heights of Ti/Pt/Au on bulk $In_{0.52}Al_{0.48}As$ is $\phi_{Bn} = 0.655$ eV and $\phi_{Bp} = 0.781$ eV. Since the MSM employs back-to-back Schottky diodes, the lowest barrier height for holes (ϕ_{Bp}) or for electrons (ϕ_{Bn}) will dominate the current. Therefore, we assume electron conduction predominates, and estimate the barrier height, ϕ_{Bn}. For the effective Richardson's constant (A^{**}) of 18 $A \cdot cm^{-2} \cdot K^{-2}$ for InAlAs given by Sadwick *et al.*,[10] we can find the barrier height using:

$$\phi_{Bn} = \frac{kT}{q} \ln\left(\frac{A^{**}T^2}{J_S}\right). \qquad (1)$$

By extrapolating the current on the I-V characteristics to zero bias and estimating the contacted area to be 1875 for 75×75 μm^2 area MSM photodiodes with 1-μm-wide electrodes and 2-μm-wide spacings, J_S, the saturation current density at zero bias is found. Using the equation above, ϕ_{Bn} for CTO and Ti/Au were estimated to be 0.47 and 0.595 eV, respectively, by using zero bias currents of 400 and 3.2 nA, respectively. The low Schottky barrier height for CTO is probably due to damage of the thin 200 Å $In_{0.52}Al_{0.48}As$ layer created during the sputtering process. Defect related tunneling through the barrier can lead to

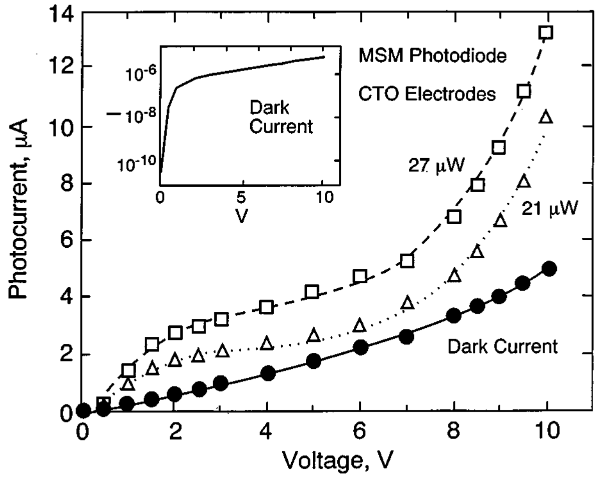

FIG. 3. Dark current and photocurrent under two arbitrary illuminations ($\lambda = 1.3$ μm from QTH lamp) for MSM photodiodes with 1 μm finger width and 2 μm spacing and active area of 75×75 μm^2 using CTO electrodes.

an effective lowering of the barrier height. By increasing the $In_{0.52}Al_{0.48}As$ cap layer thickness, the effects of sputter damage could be minimized. This will be explored in future work. At this time no intermediate metal such as Pt or Ti was inserted to improve the barrier height because initial studies showed even 50 Å of Pt transmitted only 80%–90%. The barrier height of CTO on our future MSM photodiode structure should be higher with a thicker $In_{0.52}Al_{0.48}As$ cap layer where the thickness is made greater than the sputter damage depth.

The dark current for the CTO and Ti/Au MSM photodiodes was measured, and is shown in Figs. 2 and 3. Also shown in Figs. 2 and 3 is the photocurrent measured at two arbitrary incident light levels ($\lambda = 1.3\ \mu m$). The photocurrent plotted was taken as the current measured minus the dark current. Both photodiodes exhibited a soft breakdown indicative of tunneling through the thin 200 Å $In_{0.52}Al_{0.48}As$ cap layer as the breakdown mechanism. The breakdown voltages for the CTO and Ti/Au MSM photodiodes are about 10 and 13 V, respectively. At the chosen biasing point of 10 V, the dark currents for the CTO and Ti/Au MSM photodiodes were 4.8 μA and 270 nA, respectively. It is clear that the CTO photodiode shows a much larger leakage current which linearly increases quite dramatically with increasing bias. This large leakage current and soft breakdown voltage again probably comes from defect-related tunneling.

The spectral dependence of the responsivity was analyzed using an Oriel 1000 W quartz tungsten halogen (QTH) lamp source and a monochrometer. The system response which includes the spectral dependence of the QTH lamp and all the optical components was tested using a calibrated Newport Ge photodiode.

The spectral responsivity curves were calibrated by inserting an InGaAsP diode laser in place of the QTH lamp. A small laser spot is easily obtained which is smaller than the MSM active area. Subsequent measurements of the MSM photodiode and calibrated Newport Ge photodiode yield an absolute responsivity at the laser wavelength ($\lambda = 1.3\ \mu m$). The final spectral dependent responsivity curves for the CTO and Ti/Au MSM photodiodes are then obtained using these calibration points to adjust the curves. The results are shown in Fig. 4. At the InGaAsP laser diode wavelength, the CTO and Ti/Au responsivities were 0.49 and 0.28 A/W, respectively. Clearly, the CTO demonstrates a significant improvement (~75%) for the MSM photodiode responsivity. To qualify these results, no AR coating was employed for the spacings between the MSM electrodes.

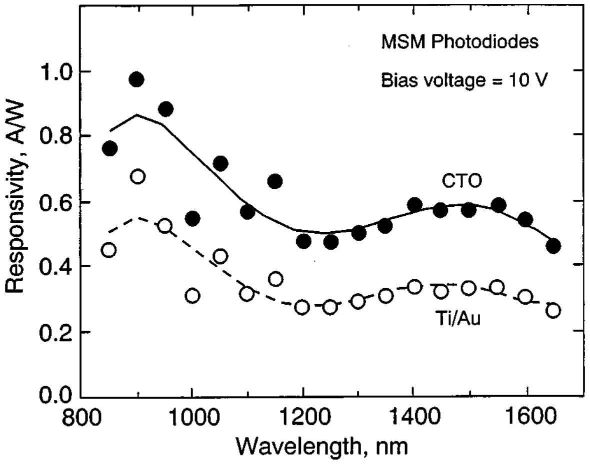

FIG. 4. Spectral responsivity of Ti/Au and CTO MSM photodiodes from 0.85 to 1.65 μm.

In summary, we have designed, fabricated and tested an $In_{0.53}Ga_{0.47}As$ MSM photodiode which uses CTO as the Schottky electrode. The CTO acts as a transparent conductor preventing shadowing of the active area. There is a marked improvement in responsivity over conventional metal Schottky electrodes.

The authors would like to thank Oriel for the white light source needed for spectral responsivity measurements. Partial support for this work was given by the University of Delaware Research Foundation (UDRF).

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