$In_{0.53}Ga_{0.47}As$ MSM Photodiodes with Transparent CTO Schottky Contacts and Digital Superlattice Grading

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***Abstract*— Metal-semiconductor-metal (MSM) photodiodes with an $In_{0.53}Ga_{0.47}As$ active region were investigated using a transparent cadmium tin oxide (CTO) layer for the interdigitated electrodes to improve the low responsivity of conventional MSM photodiodes with opaque electrodes. CTO is suitable as a Schottky contact, an optical window and an anti-reflection (AR) coating. The transparent contact prevents shadowing of the active layer by the top electrode, thus allowing greater collection of incident light. Responsivity of CTO-based MSM photodiodes with 1-μm finger widths and 2-μm finger spacings and without an AR coating between the electrodes was twice (0.62 A/W) that of a similar MSM photodiodes with Ti/Au electrodes (0.30 A/W). A thin 800 Å $In_{0.52}Al_{0.48}As$ layer was inserted below the electrodes to elevate the electrode Schottky barrier height. A digitally graded superlattice region (660 Å) was also employed to reduce carrier trapping at the $In_{0.53}Ga_{0.47}As/In_{0.52}Al_{0.48}As$ heterointerface which acts to degrade photodiode bandwidth. Bandwidth of opaque electrode MSM's was elevated nearly an order of magnitude over a previous MSM photodiode design with an abrupt heterointerface, whereas the bandwidth of transparent electrode MSM's only improved about five times, indicating resistive effects may be intervening.**

I. INTRODUCTION

METAL-SEMICONDUCTOR-METAL (MSM) photodiodes have attracted much attention recently due to their high-speed performance [1] and ease of integration [2]. MSM photodiodes have a much lower capacitance per unit area than p-i-n photodiodes, and thus are often transit time limited [3]. 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 transit time is related to the spacing between these interdigitated electrodes. MSM photodiodes are more easily integrated with pre-amplifier circuitry than p-i-n photodiodes. One reason is that MSM photodiodes do not require doping which eliminates any parasitic capacitive coupling between the photodiode and doped regions within the active transistors. Another reason is that the Schottky electrodes of the MSM photodiodes are essentially identical to the gate metallization of field effect transistors (FET).

But, MSM photodiodes suffer from very low external quantum efficiency (EQE). MSM photodiodes exhibit low EQE mainly because the metallization 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 EQE greater than 50%, for equal electrode width and spacings. Some previous investigations have explored MSM photodiodes with transparent conductors [5]–[7] but have suffered from high series resistance and/or optical absorption. Our previous studies have investigated cadmium tin oxide (CTO) which has a low resistivity and high transparency at long wavelengths as a transparent contact for $In_{0.53}Ga_{0.47}As$ p-i-n photodiodes [8] and $In_{0.53}Ga_{0.47}As$ MSM photodiodes [9], [10].

An earlier CTO MSM photodiode [9] exhibited higher leakage currents and depressed bandwidths [10]. The elevated leakage currents were attributed to sputtering damage to the thin Schottky barrier enhancement layer. The reduced bandwidth was caused by carrier pile-up at the abrupt heterointerface between the active InGaAs layer and the Schottky barrier enhancement InAlAs cap layer [11], [12]. These drawbacks were reduced significantly by increasing the overlayer thickness and employing a digitally graded superlattice region presented in this work. The overall goal of raising the MSM responsivity by eliminating shadowing of the active region was demonstrated, and digital superlattice (SL) grading was applied to an MSM photodiode with transparent electrodes for the first time. The responsivity was doubled compared to its opaque electrode counterpart.

II. EXPERIMENTAL

The MSM photodiode structure is grown by molecular beam epitaxy (MBE). The device consists of a 20-period InGaAs/InAlAs (40 Å/40 Å) superlattice (SL) buffer on a semi-insulating InP substrate, a 1.0 μm i-$In_{0.53}Ga_{0.47}As$ active region ($\sim 1.3 \times 10^{15}$ cm^{-3}), and a 660 Å digitally graded SL region. The graded SL consists of 11 periods of $In_{0.53}Ga_{0.47}As$

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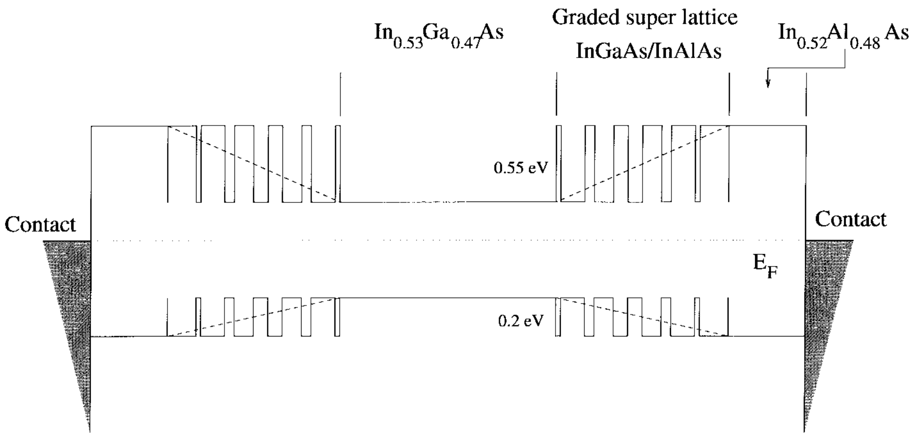


Fig. 1. A digital SL graded barrier enhancement structure is used for this study. The graded superlattice on top of the In$_{0.53}$Ga$_{0.47}$As active layer consists of alternate ultra-thin multilayers of undoped In$_{0.53}$Ga$_{0.47}$As and In$_{0.52}$Al$_{0.48}$As. As the thickness ratio varies, the effective bandgap is graded linearly in depth as shown by the dotted line in the band diagram of the unbiased MSM photodiode above.

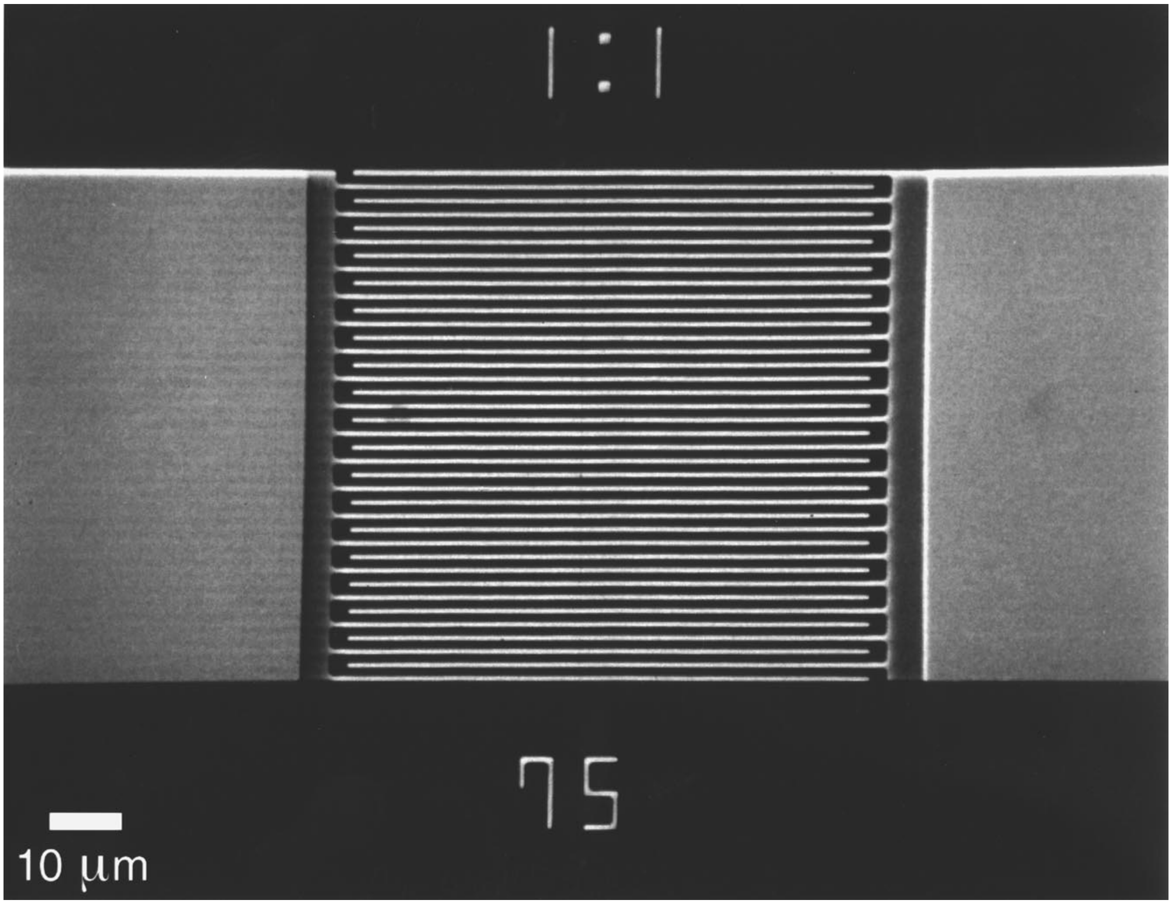


Fig. 2. A scanning electron microsope (SEM) photomicrograph of a fabricated MSM photodiode. The active area is 75×75 μm^2 with 1.0-μm wide electrodes and 1.0-μm gap spacings.

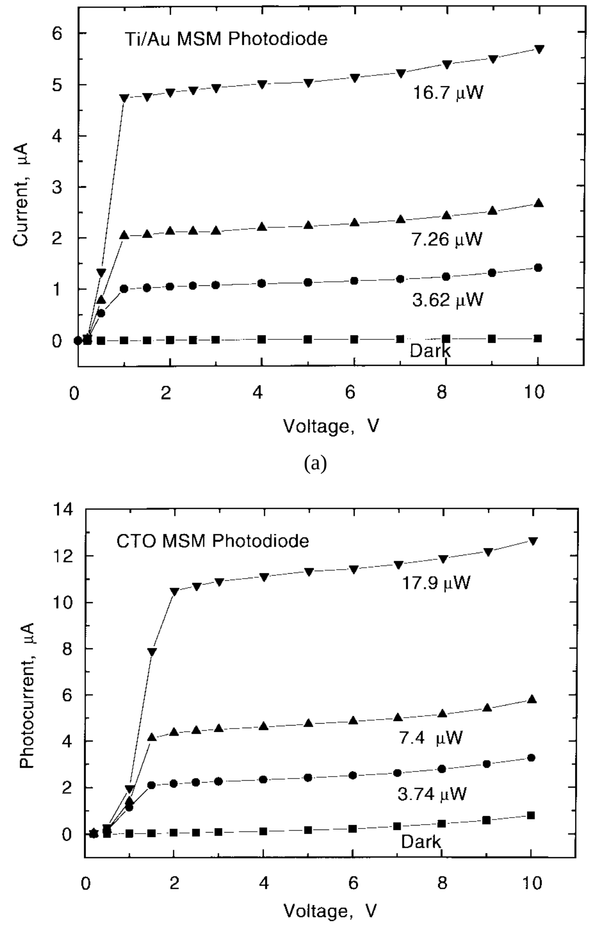
and In$_{0.52}$Al$_{0.48}$As, whereby the first period is composed of 55 Å of In$_{0.53}$Ga$_{0.47}$As and 5 Å of In$_{0.52}$Al$_{0.48}$As, and the last period is reversed with 5 Å of In$_{0.53}$Ga$_{0.47}$As and 55 Å of In$_{0.52}$Al$_{0.48}$As. The intermediary layers vary linearly between these two endpoints. The graded SL is then capped with an additional 800 Å i-In$_{0.52}$Al$_{0.48}$As Schottky barrier enhancement layer. Grading by digital superlattices effectively results in a compositionally graded bandgap, and is more readily achieved using solid source MBE. Fig. 1 shows the band diagram of the unbiased MSM photodiode structure. The grown photodiode structure was characterized by photoluminescence (PL). The low-temperature (5.5 K) PL showed a dominant excitonic peak at 0.795 eV (15 597 Å) with a full width at half maximum (FWHM) of 7.1 meV.

Both sets of MSM photodiode electrodes were defined by conventional liftoff photolithography. The deposition of the optically transparent CTO layer (2000 Å) was conducted using RF magnetron sputtering. Details of the sputtering process are reported elsewhere [9], [13]. The Ti/Au electrodes (200 Å/1500 Å) were evaporated in an e-beam evaporator. After liftoff of the MSM electrodes, thick Ti/Au pads for probing were also patterned for liftoff and deposited. The MSM photodiodes are completely planar. An MSM photodiode used in this study is shown in Fig. 2.

III. RESULTS

The dark current for the Ti/Au and CTO MSM photodiodes was measured and is shown in Fig. 3(a) and (b), respectively. The breakdown voltages for the CTO and Ti/Au MSM photodiodes were greater than 10 V. At the chosen biasing point of 10 V, the dark currents for the CTO and Ti/Au MSM photodiodes were 775 and 16 nA, respectively, which corresponds to a current density of 3.1×10^{-2} A/cm^2 and 6.4 $\times$ 10^{-4} A/cm^2, respectively. Since the bonding pads were not isolated from the device structure by a mesa etch or dielectric layer, a sizable parallel conduction path, which bypasses the active region, is possible. However, it is clear that the CTO photodiode shows a larger leakage current which increases with increasing bias. This larger leakage current and softer breakdown characteristics arises from defect-related tunneling. Some tunneling through the thin $\text{In}_{0.52}\text{Al}_{0.48}\text{As}$ seems likely, especially since the surface is expected to have a large density of defect and trap levels caused by the sputtering process through which trap-assisted tunneling could occur. However, as a result of the thicker Schottky barrier enhancement layer (800 and 660 Å SL), the dark current and breakdown voltage were greatly improved in these devices over previous MSM photodiodes with a thinner Schottky barrier enhancement layer (200 Å) [9].

Extraction of the electron and hole Schottky barrier heights (ϕ_{B_n}, ϕ_{B_p}) from an MSM photodiode is complicated by the serially connected back-to-back Schottky diodes. An analytical treatment of the current transport in MSM structures was developed by Sze *et al.* [14], and takes into account electron transport over ϕ_{B_n} and hole transport over ϕ_{B_p} when one junction is reverse-biased and the other is forward-biased. From their analysis, it is clear that if ϕ_{B_n} is much greater than ϕ_{B_p}, or vice versa, than one carrier transport will dominate. However, an approximation to the barrier heights within the MSM photodiode, resulting in an upper limit, can be obtained more simply from analysis of single Schottky diodes. From our previous studies of the Schottky barrier height on bulk n^- $\text{In}_{0.52}\text{Al}_{0.48}\text{As}$, ϕ_{B_n} was measured to be 0.634 eV for CTO and 0.636 eV for Ti [13], [15]. These measured values indicate the Schottky barrier is pinned near mid-bandgap for $\text{In}_{0.52}\text{Al}_{0.48}\text{As}$. Thus, according to Sze *et al.*, carrier transport will be bipolar and require a more rigorous solution. The effective barrier height within the MSM photodiodes is expected to be reduced below these measured bulk values since the surface of the MSM structure is actually a composite of thin $\text{In}_{0.52}\text{Al}_{0.48}\text{As}$ and underlying $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}$ which has a significantly lower bandgap.



(a)

(b)

Fig. 3. I–V characteristics under dark and several levels of incident laser illumination ($\lambda = 1.3$ μm) for 50 $\times$ 50 μm^2 InGaAs MSM photodiodes with 1-μm electrode widths and 2-μm spacing and (a) Ti/Au and (b) CTO electrodes.

Photocurrent generated under three illuminations ($\lambda = 1.3$ μm from a laser diode) is also shown in Fig. 3(a) and (b) for digital SL graded barrier enhancement InGaAs MSM photodiodes using Ti/Au and CTO electrodes. After the flat band voltage (~1–2 V), which fully depletes the active region, a fairly flat photoresponse was achieved, rising gently as the bias voltage increases. This gradual rise is due to the slight increase in the depletion region volume (laterally) leading to a larger generation current and greater detection volume. Mesa isolation of the photodiodes may avoid this effect. There is a slight saturation in EQE as the optical power is raised. An elevated EQE is observed for CTO MSM photodiodes compared with the Ti/Au MSM photodiodes.

The spectral dependence of the responsivity was analyzed using an Oriel 1000 W quartz tungtsten 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 Newport Ge photodiode. The spectral responsivity curves were calibrated by inserting an InGaAsP diode laser in place of the QTH

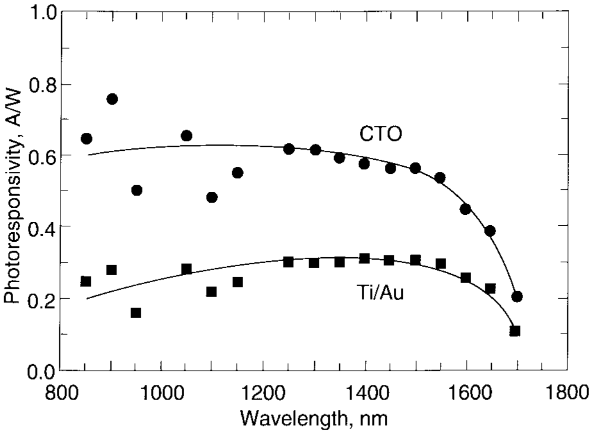


Fig. 4. Responsivity of two MSM photodiodes comparing transparent conductor (CTO) and opaque metal (Ti/Au) electrodes.

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 ($\lambda = 1.3$ μm). 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. Responsivity using 1.3-μm incident laser light was 0.62 and 0.30 A/W, respectively, for the CTO and Ti/Au MSM photodiodes. The CTO MSM photodiode shows a factor of two improvement in responsivity over the Ti/Au MSM photodiodes. The different spectral dependence of the Ti/Au and CTO MSM photodiodes in the middle regions is due to the change in transmission properties of the CTO over the wavelengths scanned.

To qualify these response results, no anti-reflection (AR) coating was employed for the spacings between the MSM electrodes resulting in ~28% of 1.3 μm light reflected from the bare $In_{0.52}Al_{0.48}As$ surface. Since the aspect ratio of electrode width to spacing is 1 : 2, then ~19% of the light is lost due to reflections between the electrodes. For a 1-μm thick active layer, EQE is limited to ~51 and ~34% for the CTO and Ti/Au MSM photodiodes, respectively. This compares favorably with the measured EQE of 59 and 29% for the CTO and Ti/Au MSM photodiodes, respectively. However, the CTO photodiodes appear to exhibit a slight photoconductive gain.

The bandwidth of the MSM photodiodes was measured using a Cascade probe station with coplanar probes and an HP 8703 Lightwave Analyzer with a 1.3-μm externally modulated laser diode which was butt coupled to the detectors via a single-mode optical fiber. Directly measured bandwidths using small signal modulation, unlike deconvolved impulse measurements which assume a Gaussian pulse, account for asymmetries in the pulse waveform due to a fast turn-on (electron component) and a slow turn-off tail (hole component). Our method leads to less impressive, but more accurate, reported bandwidths. Previous CTO and Ti/Au MSM photodiodes using abrupt barrier enhancement structures demonstrated 3-dB bandwidths of 0.3 and 0.8 GHz, respectively [10]. However, digital grading of the transition facilitated better carrier extraction resulting in increased bandwidths. The highest measured bandwidths were 1.3 and 7.1 GHz, respectively, for CTO and Ti/Au MSM photodiodes. A large difference in the imput impedance of Ti/Au and CTO MSM photodiodes affected the microwave calibration, and lead to some uncertainties. Thus, the measured bandwidth of the CTO MSM photodiodes should be taken as a lower limit.

The Ti/Au MSM photodiodes showed a marked improvement in bandwidth with SL grading probably because they are transit time limited, whereas limited improvement occurs with CTO electrodes indicating other effects play a significant role. The slower response of the MSM photodiode with CTO electrodes is most likely caused by: 1) the longer distance that carriers must travel for electron-hole pairs generated below the transparent electrodes, and 2) the significant series resistance of the CTO electrodes leading to RC time constant effects.

Subsequent S-parameter measurements of these MSM diodes was performed with a 10 V bias and no illumination via an HP8510 network analyzer [16]. The S-parameter data was then modeled using the HPEESOF package LIBRA. A model was proposed which treated each contact as a Schottky diode, one reverse biased and the other forward biased, and with a resistive capacitive network inserted between the two Schottky contacts. From the lumped element models extracted, a large series resistance for the CTO MSM photodiodes was found which may lead these devices to be RC time constant limited, not transit time limited. This may account for the limited bandwidth enhancement of CTO MSM photodiodes using SL grading at the heterointerface.

IV. CONCLUSION

In summary, we have designed, fabricated, and tested $In_{0.53}Ga_{0.47}As$ MSM photodiodes which use CTO as the electrode fingers. The CTO acts as a transparent conductor preventing shadowing of the active area. There is a marked improvement in responsivity (100%) over conventional opaque metal Schottky electrodes. Two InAlAs barrier enhancement layer versions were used. A higher bandwidth was observed for the digitally graded SL barrier enhancement MSM photodiodes.

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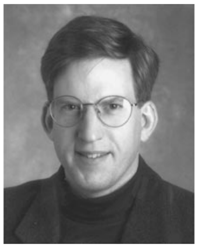

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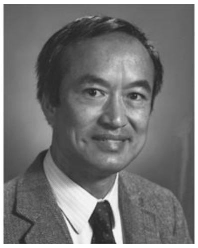
Dr. Sivco was a co-recipient of the Newcomb Cleveland Prize, AAAS 1994, the British Electronic Letters Premimum Award, 1995, and a 1996 Technology of the Year Award from *Industry Week Magazine*.



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Dr. Cho's work has earned him the recognition of his peers as evidenced by many awards from technical and professional societies. Among these are the 1982 International Prize for New Materials from the American Physical Society, the 1987 Solid-State Science and Technology Medal of the Electrochemical Society, the 1988 World Materials Congress Award, the 1990 International Crystal Growth Award of the American Association for Crystal Growth, the 1993 National Medal of Science, presented by President Clinton, the 1994 IEEE Medal of Honor, and the 1995 C & C (Computer and Communications) Prize, Japan. He is a member of the National Academy of Engineering, the National Academy of Sciences, and the American Philosophical Society.