

# Novel Metal–Semiconductor–Metal Photodetectors on Bulk Semi-Insulating Indium Phosphide

J. W. Palmer, *Member, IEEE*, W. A. Anderson, *Senior Member, IEEE*, and A. Cartwright

**Abstract**—Depositing Pd or Au on InP at substrate temperatures near 77 K (LT) has previously been found to significantly reduce the interaction between the metal and semiconductor upon formation of the interface. In this letter, this technique was used to fabricate metal–semiconductor–metal photodetectors (MSMPD's) on semi-insulating (SI) InP substrates with superior characteristics compared to detectors formed using standard room temperature (RT) metal deposition. Detectors having a LT-Pd–SI–InP structure had a dark current of 80 nA at 5 V, which was a factor of 4 lower than the dark current of conventional MSMPD's. Additionally, LT-Pd–SI–InP MSMPD's exhibited excellent saturation characteristics and a responsivity of 0.75 A/W. Detectors with an indium–tin–oxide (ITO)–LT–Au (200 Å)–SI–InP structure had a higher responsivity of 1.0 A/W, due to the relative transparency of this metallization. In contrast, MSMPD's with RT metallizations had poor saturation characteristics, consistent with the results of others. The difference in the illuminated characteristics of MSMPD's with RT and LT metallizations was due to a change in the internal photoconductive gain mechanism. In RT detectors, hole trapping at interface states near the cathode dominated the gain mechanism. In LT detectors, the difference in carrier transit-times dominated.

**Index Terms**—Indium phosphide (InP), photodetector, Schottky.

## I. INTRODUCTION

METAL–SEMICONDUCTOR–METAL photodetectors (MSMPD's) are prime candidates for integration into optoelectronic circuits. They are easy to fabricate, compatible with planar processing techniques, and have very high switching speeds. MSMPD's usually consist of two rectifying contacts with interdigitated fingers and have a transit-time limited photocurrent [1]. Ideally, when the applied voltage is high enough that the carrier transit-time is less than the carrier lifetime, the photocurrent saturates and the detector acts like a current source. However, most MSMPD's reported have a quasi-saturated regime in which the photocurrent increases slowly with the applied voltage. Such behavior indicates the presence of an internal gain [2], and the extent to which this occurs varies depending on the details of the device fabrication.

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Much work has been done with GaAs and InGaAs MSMPD's operating at wavelengths near 800 and 1300 nm, respectively. GaAs detectors have been fabricated with good saturation characteristics [3], [4]. Typical parameters for these detectors are a responsivity (R) near 0.2 A/W, dark currents on the order of 10 nA, and photocurrent saturation at biases less than 1–2 V for electrode spacings less than 5  $\mu\text{m}$ . Such detectors have been successfully incorporated into GaAs integrated digital photoreceivers [5], [6]. MSMPD's on InGaAs suffer the problem that standard Schottky contacts to InGaAs have a very low electron barrier height, resulting in unacceptably large dark currents. One method used to overcome this problem is to place a higher bandgap material between the InGaAs and the metallization, such as InP [7] or InAlAs [8]. In this manner, dark currents in the 10–500-nA range have been attained.

Compared to GaAs and InGaAs, relatively little has been written about MSMPD's on bulk InP. Standard RT metallizations to InP result in a low electron barrier height of about 0.5 eV on undoped material ( $N_D = 10^{15} \text{ cm}^{-3}$ ) due to interactions between the metal and InP. One paper [9] reported use of a pseudomorphic GaInP layer on InP ( $N_D < 10^{16} \text{ cm}^{-3}$ ) to increase the electron barrier height and obtain a dark current below 100 nA at 29 V for a 40  $\mu\text{m} \times 40 \mu\text{m}$  device. Another paper [10] reported a MSMPD using a standard Au metallization on semi-insulating (SI) InP to attain a dark current of 10 nA at 10 V for a 50  $\mu\text{m} \times 50 \mu\text{m}$  device. However, this detector had a quasi-saturated photocurrent regime with a very strong bias dependence. Such a bias dependence is usually attributed to a photoconductive gain mechanism caused by hole accumulation near the cathode [2], [11]. The resulting buildup of positive charge lowers the barrier height to electrons at the cathode, causing electron injection. The accumulation of holes is due either to long-lifetime traps at the metal–InP interface or the difference in transit times between the electrons and holes, causing photogenerated electrons to be swept out of the semiconductor much faster than the holes. Standard metallizations to InP result in the creation of interface states because of chemical reactions between the metal and the semiconductor [12]. Therefore, hole trapping probably occurs at the cathode of InP MSMPD's fabricated in this manner. Recently, it was found that depositing Pd or Au on InP using substrate temperatures near 77 K (LT) significantly reduces the interaction between the metal and InP [13], dramatically increasing the electron barrier height to 0.9 eV [14]. The goal of this project was to fabricate InP MSMPD's using a LT metallization to reduce carrier trapping

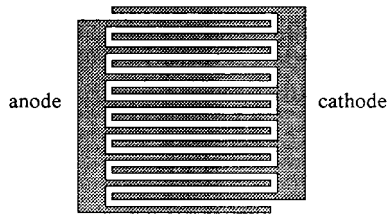


Fig. 1. Plan-view sketch of a MSMPD. Line width  $\times$  line spacing =  $3 \mu\text{m} \times 3 \mu\text{m}$ , device area =  $200 \mu\text{m} \times 200 \mu\text{m}$ .

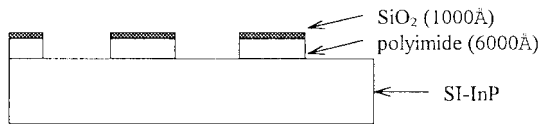


Fig. 2. Cross section of the liftoff mask prior to metallization.

at the metal–semiconductor interfaces, and to measure how this affected the dark and illuminated device characteristics.

## II. EXPERIMENT

MSMPD's were fabricated on bulk SI–InP using three different types of metallizations. In all three cases, the SI–InP had a resistivity of  $10^7 \Omega\cdot\text{cm}$ , and the active area of the devices was  $200 \mu\text{m} \times 200 \mu\text{m}$  with linewidths and line spacings of  $3 \mu\text{m}$ . A plan-view sketch of the metallizations is shown in Fig. 1.

The first type of metallization used was Pd deposited at a substrate temperature near 77 K. Standard liftoff could not be used for the LT-Pd metallization because photoresist cannot withstand the thermal stresses present during the deposition. Instead, a bilayer polyimide–SiO<sub>2</sub> liftoff mask was used. First, the SI–InP was cleaned in acetone, methanol, and deionized H<sub>2</sub>O, etched in H<sub>2</sub>SO<sub>4</sub>:H<sub>2</sub>O<sub>2</sub>:H<sub>2</sub>O (2:1:1) for 10 min, etched in HF:H<sub>2</sub>O (1:1) for 1 min, rinsed, and dried in N<sub>2</sub> gas. A polyimide layer, 0.6  $\mu\text{m}$  thick, was then spun on and cured at 170 °C, followed by deposition of a SiO<sub>2</sub> layer 0.1- $\mu\text{m}$  thick by plasma-enhanced-chemical-vapor-deposition (PECVD). Photoresist was then applied and standard lithography was used to pattern the grid lines. Reactive-ion-etching (RIE) in CHF<sub>3</sub> was used to transfer the metallization pattern to the SiO<sub>2</sub>, followed by RIE in O<sub>2</sub>, which simultaneously patterned the polyimide and removed the photoresist. Fig. 2 shows a cross-sectional view of a liftoff layer ready for metallization. Immediately prior to the LT metal deposition, the samples were etched in HCl:H<sub>2</sub>O (1:10) for 1 min to remove any damage to the InP left by RIE. The LT-Pd was then deposited by thermal evaporation using a base pressure in the  $10^{-8}$  torr range and a substrate temperature near 77 K. Liftoff was done in Shipley 1165 remover, which dissolved the polyimide over a period of several hours.

The second type of metallization used was Pd deposited at room temperature (RT). Except for the substrate temperature, the procedure for fabricating this type of detector was identical to that for the LT-Pd/SI–InP detector described above. The RT-Pd/SI–InP detectors were fabricated only for the purpose of comparison. The cross-sectional structure of both the LT-Pd/SI–InP and the RT-Pd/SI–InP MSMPD's is shown in Fig. 3.

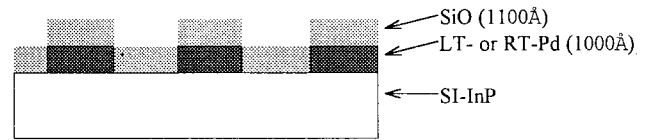


Fig. 3. Cross section of a MSMPD with a Pd/SI–InP structure.

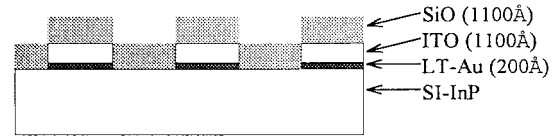


Fig. 4. Cross section of a MSMPD with an ITO/LT–Au–SI–InP structure.

The third type of detector fabricated had an ITO (800 Å)/LT–Au (200 Å)/SI–InP structure, shown in Fig. 4. One of the major problems with MSMPD's is that the grid metallization usually prevents half of the incident light from entering the semiconductor. The structure shown in Fig. 4 was designed to reduce the severity of this problem. First, a thin LT–Au deposition established a quality MS interface to the InP. The sample was then transferred from the LT deposition system to a sputtering system, where ITO was deposited using a substrate temperature of 150 °C. The elevated substrate temperature was necessary to attain a conductive, transparent, ITO film. The result was a metallization which was more transparent to incoming photons, while maintaining the integrity of the metal–InP interface.

Finally, a SiO antireflection coating, 1100-Å thick, was deposited on all three types of detectors to attain zero-reflection at  $\lambda = 840 \text{ nm}$  over the bare InP between cathode and anode. The photoresponse of the detectors was measured using a continuous-wave (CW) Spectra Physics Tsunami Ti:Sapphire laser operating at  $\lambda = 840 \text{ nm}$ . The beam was passed through a half-wave-plate, a polarizer, and then a lens which focused it to a 100  $\mu\text{m}$  full-width at half-maximum spot size on the center of a detector. By adjusting the halfwave-plate, the incident power of the polarized light was controlled.

## III. RESULTS AND DISCUSSION

Fig. 5 is the dark-current characteristics of MSMPD's having LT-Pd and RT-Pd grids. The dark current of the LT-Pd detector is a factor of 4 lower than that of the RT-Pd device at all voltages, with a value of 400 nA at 10 V. The dark current in MSMPD's consists of a combination of electrons injected at the cathode and holes injected at the anode [15]. Since a RT metallization on InP has a low-electron barrier height, the dark current in this case will be due primarily to electron injection at the cathode. However, use of a LT-Pd metallization increases the barrier height to electrons, or decreases the barrier height to holes. Therefore, the dark current of the LT-Pd devices should have a larger component due to hole injection at the anode, and a smaller component due to electron injection at the cathode. The overall effect was that the total dark current in the LT-Pd devices was slightly lower than in RT-Pd devices.

Fig. 6 is the illuminated characteristics of a detector having a LT-Pd metallization. Excellent saturation characteristics were

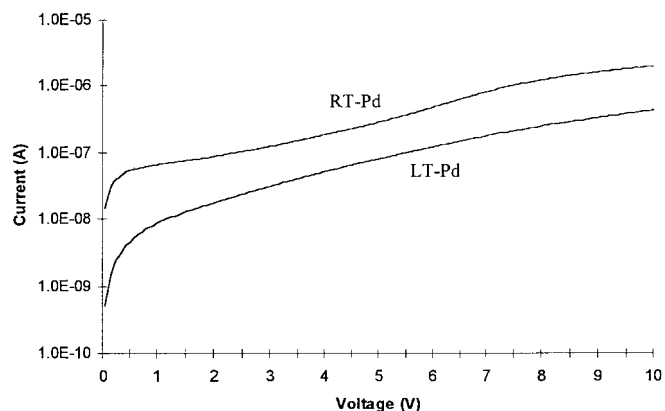


Fig. 5. Dark current versus voltage for SI-InP MSMPD's having LT-Pd and RT-Pd metallizations.

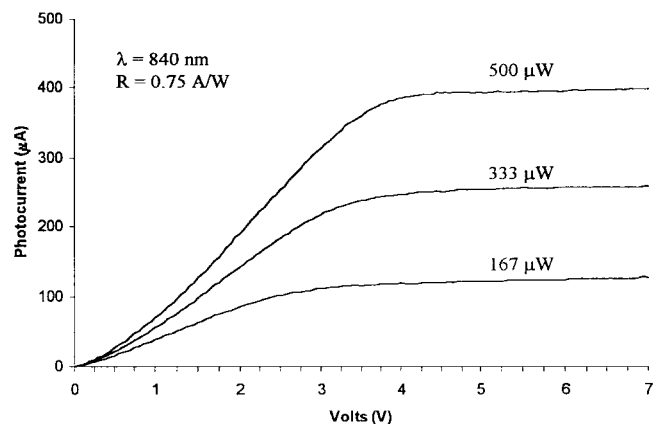


Fig. 6. Illuminated characteristic of a LT-Pd/SI-InP MSMPD.

obtained, with  $R = 0.75$  A/W. This corresponds to an external quantum efficiency of 1.1 electron-hole pairs/photon. Since half of the incident photons were lost to grid shading, it is clear that the detector had a bias-independent gain of about 2. In comparison, devices having a RT-Pd metallization exhibited a strong bias dependence of the photocurrent in the quasisaturated regime similar to the results of others [10].

For an ITO/LT-Au-SI-InP structure, a high responsivity of 1.0 A/W was obtained, which is a 33% improvement over the responsivity of a detector with a LT-Pd metallization.

The difference between the illuminated characteristics of detectors having LT and RT metallizations is related to a change in the gain mechanism. The only difference in the fabrication of the RT and LT detectors was the substrate temperature used during metal deposition. The RT metallization results in a strong chemical interaction between the metal and InP, creating interface states that may trap holes in the vicinity of the cathode. This carrier trapping dominates the photoconductive gain mechanism, and the illuminated characteristic of MSMPD's having RT metal contacts. The LT metallization nearly eliminates the chemical reaction between the metal and InP, resulting in a very abrupt metal-InP interface [13]. In this case, hole accumulation at the cathode is probably due to the transit-time differences between electrons and holes, resulting in improved gain characteristics.

#### IV. CONCLUSION

Novel MSMPD's were fabricated on SI-InP using a LT-Pd and an ITO/LT-Au metallization. The detectors had good saturation characteristics and high responsivities of 0.75 and 1.0 A/W, respectively. The higher responsivity in the ITO case was due to a more transparent grid metallization, allowing more photons to enter the semiconductor. These improved characteristics, relative to RT fabricated devices, were attributed to the abrupt metal-InP interface that results when a LT deposition is used. It is believed that the photoconductive gain mechanism present in these detectors is due to the difference in carrier transit times.

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